SAN FRANCISCO ESTUARY & WATERSHED SCIENCE
Sponsored by the Delta Science Program and the UC Davis John Muir Institute of the Environment

SPECIAL ISSUE: THE STATE OF BAY–DELTA SCIENCE 2016, PART 3

An Overview of Multi-Dimensional Models of the Sacramento–San Joaquin Delta

Michael L. MacWilliams,*[1] Eli S. Ateljevich,[2] Stephen G. Monismith,[3] and Chris Enright[4]

Volume 14, Issue 4 | Article 2
doi: http://dx.doi.org/10.15447/sfews.2016v14iss4art2

* Corresponding author: *mmacwilliams@anchorqea.com*
1 Anchor QEA, LLC
San Francisco, CA 94111 USA
2 California Department of Water Resources
Sacramento, CA 95814 USA
3 Dept. of Civil and Environmental Engineering,
Stanford University
Stanford, CA 94305 USA
4 Delta Stewardship Council
Sacramento, CA 95814 USA

ABSTRACT

Over the past 15 years, the development and application of multi-dimensional hydrodynamic models in San Francisco Bay and the Sacramento–San Joaquin Delta has transformed our ability to analyze and understand the underlying physics of the system. Initial applications of three-dimensional models focused primarily on salt intrusion, and provided a valuable resource for investigating how sea level rise and levee failures in the Delta could influence water quality in the Delta under future conditions. However, multi-dimensional models have also provided significant insights into some of the fundamental biological relationships that have shaped our thinking about the system by exploring the relationship among X2, flow, fish abundance, and the low salinity zone. Through the coupling of multi-dimensional models with wind wave and sediment transport models, it has been possible to move beyond salinity to understand how large-scale changes to the system are likely to affect sediment dynamics, and to assess the potential effects on species that rely on turbidity for habitat. Lastly, the coupling of multi-dimensional hydrodynamic models with particle tracking models has led to advances in our thinking about residence time, the retention of food organisms in the estuary, the effect of south Delta exports on larval entrainment, and the pathways and behaviors of salmonids that travel through the Delta. This paper provides an overview of these recent advances and how they have increased our understanding of the distribution and movement of fish and food organisms. The applications presented serve as a guide to the current state of the science of Delta modeling and provide examples of how we can use multi-dimensional models to predict how future Delta conditions will affect both fish and water supply.

KEY WORDS

Hydrodynamic modeling, UnTRIM, SUNTANS, SCHISM, RMA2, Delft3D, low salinity zone, X2, fish movement, fish distribution, food organisms, water supply, future conditions.

INTRODUCTION

It is notable that when the State of Bay–Delta Science 2008 (Healey et al. 2008a) was published, newly emerging multi-dimensional models of the Sacramento–San Joaquin Delta (Delta) merited only a short discussion in the chapter dealing with water

supply (Healey et al. 2008b). As a result of significant advances in both computational power and the development of multi-dimensional models over the past decade, multi-dimensional models of the Delta have been applied much more widely, and have proved their usefulness in helping us to better understand not just issues relating to water supply, but also the complex interactions between physics and biology that drive the distribution and movement of fish and food organisms.

Before delving into the details of multi-dimensional physical modeling, it is important to recognize at the outset that the ability of any model to predict physical, chemical, and biological processes varies, and strongly depends on what is being modeled and on the time-scale of interest. Roughly speaking, the shorter the time-scale and the more physical the process, the better the model will perform (Figure 1). For example, tidal water levels and currents can generally be calculated with a high degree of precision. Conversely, modeling biological or ecological processes that evolve over longer time scales, is a significantly more challenging modeling task. On this end of the spectrum, predicting how a marsh will change over several decades as a result of the interactions among sediments, vegetation, and fauna remains a remarkably hard modeling challenge, particularly given the uncertainty with how the forcing variables will change in the future.

The challenge in modeling physical processes in the Delta is its complexity. Flows in this geometrically complex domain are influenced by tides; winds; freshwater inflows from tributaries that are influenced by rain, snowmelt, and reservoir operations; in-Delta agricultural diversions and return flows; the construction and operation of temporary barriers; permanent operable control gates, and the operation of the Central Valley Project (CVP) and State Water Project (SWP) exports. Some aspects of this system can be represented by water accounting models such as CalSIM II (Draper et al. 2004; CDWR 2013, Sections A and B), which operates on a monthly time-step to balance the requirements of reservoir storage and flow releases, operation of the SWP and CVP exports, and the maintenance of applicable water quality objectives. Other aspects of the system, such as salinity intrusion, result from complex interactions of tides, wind, and freshwater outflow, and require a three-dimensional (3-D) model operating on a short time-step to accurately represent vertical and horizontal circulation processes. Thus, the type and complexity of the model that is needed to model a system depends to a large degree on the type of processes being evaluated, and the questions that need to be answered. Table 1 provides an overview of some of the primary physical processes that are important drivers in the Delta, and an assessment of whether the processes are explicitly represented by 1-D, 2-D, and 3-D models. In Table 1, and throughout this chapter, we use 2-D to indicate depth-averaged 2-D models; however, we recognize that for some applications 2-D can also indicate

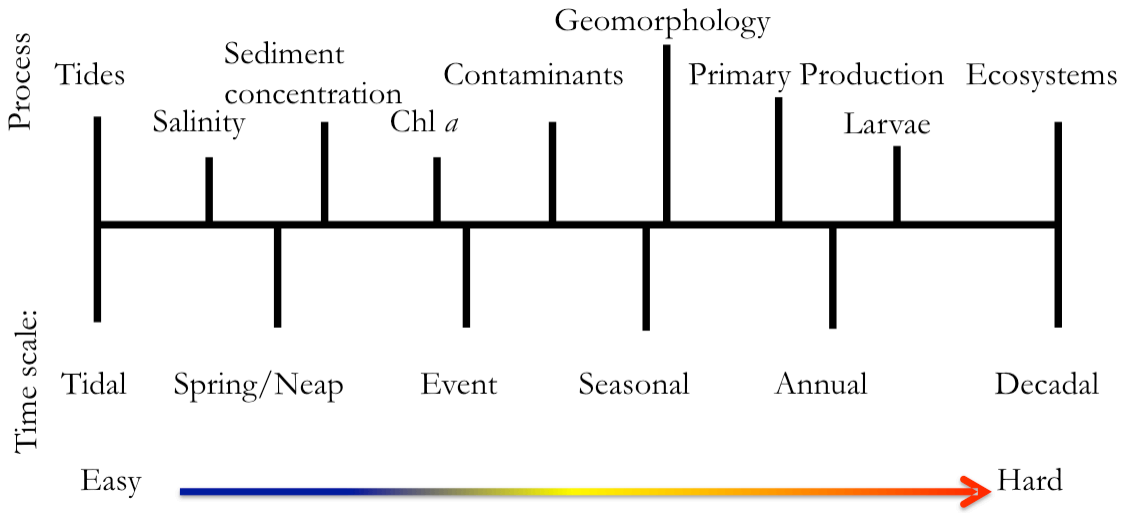

Figure 1 Schematic view of the spectrum of modeling physical and biological processes in the Delta

Table 1 Physical processes, and an assessment ability of 1-D, 2-D, and 3-D models to represent these processes. Key: green shading = yes; yellow shading = partially; red shading = no.

Process name	1-D	2-D	3-D
Tides and water levels			
Net flow			
Mixing at junctions			
Mixing in open water embayments			
Tidal trapping			
Wind-driven circulation			
Wind waves			
Gravitational circulation / salinity intrusion			
Secondary circulation			
Sediment routing			
Erosion and deposition / morphological evolution			
Temperature (depth-averaged)			
Temperature stratification			
Passive particle tracking (larva)			
Active particle tracking (fish)			

laterally-averaged models. The ability of a model to represent some processes depends both on resolution and dimensionality, so for some processes listed in Table 1, multiple colors are shown to indicate that the ability of a class of models to represent this process may also be resolution and algorithm-dependent. Although this type of assessment is somewhat subjective, Table 1 can serve as a resource for selecting the type and dimensionality of model that may be necessary to evaluate specific types of applications.

When a model cannot (because of dimensionality or resolution) or does not (because of numerical formulation) represent a process, that process can often be successfully parameterized using integrated processes, simplified closure terms or approximations, some of which involve tunable numerical coefficients. One example of this is the so-called "diffusion analogy" described by Fischer et al. (1979) for dispersion in a 1-D model such as DSM2 in order to accurately represent salinity intrusion. In this case, the primary mechanisms responsible for salinity intrusion include gravitational circulation (vertical), lateral shear, and tidal trapping (horizontal), which are 3-D and 2-D processes. Instead of modeling these directly, dispersion parameters are tuned on each channel segment to represent salt-intrusion processes that are not resolved in 1-D. In 3-D, cross-sectional variations leading to dispersion are modeled explicitly. A more modest diffusion analogy is still made in 3-D, in the form of turbulence closures of varying complexity that determine rates of vertical mixing (e.g., see Wang et al. 2011). Horizontal turbulent mixing is generally neglected because it has almost always been found to be weaker than numerical diffusion associated with the numerical scheme(s) used to represent advection (Gross et al 1999; Chua and Fringer 2011).

Although physical simplification and approximation can be effective for simulating conditions within historical bounds, they limit the predictive capability of the model if the system changes significantly. For example, a 1-D model cannot be used to determine the effects of sea level rise since the dispersion coefficients tuned for existing sea levels would not be applicable under those future conditions. To work around this limitation for the Bay Delta Conservation Plan (BDCP) project, 3-D model simulations (MacWilliams and Gross 2010) were used to simulate salinity under future conditions with sea level rise, and the dispersion coefficients in the 1-D model in the western Delta were recalibrated to match the

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

salinity intrusion predicted by the 3-D model (CDWR 2013). The alterations were modest, and in this way, exploration was possible of an 80-year hydrology under scenarios that incorporated the effects of sea level rise on salinity intrusion. Within the design community, such multifidelity combinations of detailed and simplified models of physics have been formalized and exploited (see Robinson et al. 2008 and references therein); in the Bay–Delta such an approach may be a necessity in cases where insights arising from multi-dimensional modeling of secondary flows need to be scaled to the full domain and analyzed for effects over decades.

Because multi-dimensional models do not rely as heavily on tuning parameters and instead represent the inherent physics of the system, they are often more suitable for evaluating the effects of significant changes to the system. Of course, the internal details and resolution have to be correct in order for the physicality argument to hold, and often some of the specific sub-processes in a 3-D model are hard to validate or require study-specific considerations and field study. An example of this described below for Franks Tract would be the applicability of standard estuarine turbulence, which is well studied and appropriate in the stratified lower estuary but isn't particularly tailored for a shallow, vegetation-clogged channel or open water body. One other noteworthy challenge to accurate 3-D modeling is the spatial and temporal variability in bottom drag associated with mobile beds. For example, Fong et al. (2009) found that the bottom drag coefficient in Threemile Slough for flow from the Sacramento River into the San Joaquin River was three times larger than for the flow in the opposite direction, indicating a complex interaction of tidal currents and bedform morphology that presumably varies on sub-tidal and seasonal time scales.

The increased use of multi-dimensional models reflects advances in modeling made since the 2010 Interagency Ecological Program (IEP) modeling review (Blumberg et al. 2010). Worldwide, the estuarine modeling community has trended towards the use of unstructured (sometimes adaptive) meshes and semi-implicit algorithms that allow cross-scale, multi-year, hydrostatic circulation studies at locally medium resolution over a domain the size of the full Bay–Delta. Recent work continues on higher fidelity algorithms, including higher-order algorithms for problems that involve fronts or eddying regimes and non-hydrostatic modeling of phenomena such as secondary circulation and internal waves. More explicit representations of turbulence such as Large Eddy Simulation (LES) or even Direct Numerical Simulation (DNS) are also becoming more computationally feasible in models that cover smaller domains. We expect more near-field applications of higher-fidelity modeling to be a notable contribution in the next edition of the State of Bay–Delta Science, but will focus here on the more commonly applied 1-D, 2-D, and 3-D models that represent the state-of-the-art of modeling in the estuary, where flow is assumed to be hydrostatic and Reynolds-averaged. At the other end of the spectrum, developers and users of circulation-scale 3-D models in the last 5 years have showcased coarsening strategies such as low horizontal-resolution meshes with subgrid bathymetry (Casulli 2009; MacWilliams et al. 2016) and adaptive vertical meshing (Zhang et al. 2015). The demand for these types of features underscores the limiting role computational cost still plays, particularly for simulating decadal or longer periods in 3-D. In developing a multi-dimensional numerical model, there are many important decisions that must be made relating to spatial and time accuracy, stability, energy and momentum conservation, volume and mass conservation, grid structure, and where variables are defined on the grid. Although these aspects of numerical methods are critically important in developing numerical models, they are beyond the scope of this paper. Details about the numerical methods used in each model discussed below can be found in the references cited for each model.

BAY–DELTA MULTI-DIMENSIONAL MODELING BACKGROUND

Hydrodynamic modeling of the Delta started in earnest in the late 1970s when under U.S. Bureau of Reclamation (USBR) contract, the late Professor Hugo B. Fischer of the University of California, Berkeley, developed what is now known as the Fischer Delta Model (FDM), a model that represented the Delta as a network of 1-D channels. Later, the California Department of Water Resources (CDWR) developed its own similar 1-D model, DSM2, to which a particle-

tracking model was added. DSM2 is still widely used in planning simulations for the Delta. The model enjoys a wide user base, couples well to the statewide planning model CalSIM II, routes water through the Delta accurately over a wide range of forcing, and because of its ubiquity and speed has perhaps the best understood performance over decades. DSM2 is still widely used for contemporary applications, including the California Water Fix Biological Assessment (CDWR 2016a), and for quantifying benefits or adverse effects that could result from water storage projects proposed for the Water Storage Investment Program (CWC 2016). In modern usage, the DSM2 model is often modified or informed by multi-dimensional models in areas such as sea level rise that involve coupling to the ocean and complex circulation.

Multi-dimensional modeling of the Delta began in the mid-1990s with applications of both RMA10 (DeGeorge 1996) and TRIM2D (Monsen 2000), although earlier 2-D models of Suisun Bay (Smith and Cheng 1987) and in particular Burau et al. (1993) should be noted. Some of the earliest multi-dimensional modeling of San Francisco Bay (bay) was done with the structured grid TRIM2D and TRIM3D models (Casulli and Cheng 1992; Casulli and Cattani 1994). TRIM2D was used in the San Francisco Bay Physical Oceanographic Real-Time System (SFPORTS) for many years (Cheng and Smith 1998) and was applied to the Delta by Monsen (2000).

One of the earliest demonstrations of the power of multi-dimensional models to affect conceptual thinking about how the Bay–Delta physically works is the 2-D (depth-averaged) modeling of Suisun Bay discussed in Burau et al. (1993). Using the TRIM2D model (Cheng et al. 1993), strong horizontal mixing associated with channel–shoal velocity gradients was shown to rapidly mix scalars that might serve to mark a nominal estuarine turbidity maximum (ETM), suggesting that the classical picture of an ETM does not apply to Suisun Bay. This was an important factor in leading the U.S. Environmental Protection Agency (USEPA) flow workshops in the early 1990s to focus on the general aspects of how flow and salinity were related, rather than attempting to look at detailed management of the position of an ETM as had originally been proposed. Moreover, the striking visuals of the model results that Jon Burau presented (then and more recently) also played a role in shifting the conceptual understanding of Delta hydrodynamics away from one concerned only with sub-tidal, approximately riverine flows to one in which tidal time-scale variability is dominant. Similarly, 2-D finite element modeling of the salinity response to levee failure done by Resource Management Associates, Inc. (RMA) for the Delta Risk Management Study (DRMS) dramatically illustrated the risk posed by earthquakes to the use of the Delta as a water conveyance (CDWR 2009).

An important aspect of a multi-dimensional model application is the fact that it can lead to significant insights about system-level functioning. For example, TRIM2D modeling by Monsen et al. (2007) showed how the contributions of various sources of water to the Delta (e.g., the Sacramento River or the San Joaquin River) varied with position within the Delta and with different combinations of export pumping rate, gate operation, and barrier placement. Using the same model, Monsen (2000) also noted that closure of the Delta Cross Channel (DCC) did not eliminate entrainment into the pumps of particles (e.g., small fish) carried down the Sacramento River towards Suisun Bay; instead, it shifted the path of these particles to the pumps through Threemile Slough rather than through the DCC.

Notably, much of this earlier modeling was computationally constrained. For example, the 50-m Cartesian finite difference grid used by Monsen (2000) tended to lead to unrealistically slow flows in many of the smaller channels of the Delta that could not be resolved on a 50-m grid. Similarly, Gross et al. (2009) relied on a “false Delta” to represent the Sacramento–San Joaquin Delta in their model of the bay because the Delta could not be represented on the 200-m grid that was necessary for computationally feasible 3-D simulations of the San Francisco Estuary (estuary). Moreover, because of limited disk storage space for model output, biogeochemical or individually based models of organisms needed to be coupled directly to the hydrodynamic model. Now, with the easy availability of relatively inexpensive, powerful desktop computing, routine use of medium-sized clusters, and very inexpensive disk storage, much larger and more detailed grids can be run, with the results archived for use and re-use with other models, such

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

as the off-line coupling with particle-tracking models (e.g., Gross et al. 2010; Kimmerer et al. 2014). The result of these technological advances—as well as the introduction of unstructured grids that permit high resolution in areas of interest while allowing much coarser grids away from the area of interest—has facilitated computing flows in a domain that extends from the Gulf of the Farallones to riverine reaches of the Sacramento and San Joaquin rivers while still resolving the relatively narrow channels that make up much of the Delta (e.g., MacWilliams et al. 2015). Applications of these types, and the important lessons learned about the system from model application, are described in the following sections.

Because of the complexity and small size of many channels in the Delta, a finer grid resolution is needed to resolve these channels than is needed in other portions of the bay. The application of unstructured grids allows for the use of the finer resolution necessary to resolve small channels in the Delta, while using larger grid cells in the broader areas of the bay. Thus, the development and application of unstructured grid models such as UnTRIM, SUNTANS, SCHISM, RMA2, and Delft 3D FM led to the development and application of multi-dimensional models that span all of the bay and the entire Delta.

UnTRIM

UnTRIM (Unstructured nonlinear Tidal Residual Intertidal Mudflat) is a 3-D hydrodynamic numerical model that solves the Navier–Stokes equations on an unstructured horizontal grid and z-level vertical grid. The governing equations are discretized using a finite difference–finite volume algorithm. Although UnTRIM is a proprietary model, a complete description of the governing equations, numerical discretization, and numerical properties of UnTRIM are provided in Casulli and Zanolli (2002, 2005), Casulli (1999, 2009), and Casulli and Walters (2000). The most recent version of UnTRIM introduced "subgrid" bathymetry, which allows the bathymetry to be applied within each grid cell and on each grid face at a resolution higher than the hydrodynamic model grid itself (Casulli 2009; MacWilliams et al. 2016). The use of subgrid bathymetry allows for accurate representation of channel geometry with larger grid cells (which allow for larger time-steps) and relaxes some constraints on grid quality since grid lines no longer need to follow the coastline (since grid cells can be partially wet).

The UnTRIM hydrodynamic model has been implemented in the bay and Delta to simulate tides, inflows, and water diversions; water surface elevations; 3-D velocities; and salinity throughout the Bay–Delta system (MacWilliams et al. 2015). The UnTRIM Bay–Delta model was the first 3-D model applied to the Bay–Delta system that spanned the entire estuary from the Pacific Ocean through the Sacramento River and the San Joaquin River (MacWilliams et al. 2007, 2008, 2009, 2015). The UnTRIM Bay–Delta model has been applied as part of the Delta Risk Management Strategy (MacWilliams and Gross 2007), several studies to evaluate the mechanisms behind the Pelagic Organism Decline (e.g., MacWilliams et al. 2008), and the Bay Delta Conservation Plan (MacWilliams and Gross 2010). The UnTRIM Bay–Delta model has also been applied for a range of studies by the U.S. Army Corps of Engineers (MacWilliams and Cheng 2007; MacWilliams et al. 2009, 2012a, 2014).

The UnTRIM Bay–Delta model has also been coupled with the Simulated WAves Nearshore (SWAN) wave model (Booij et al 1999; SWAN Team 2009) and the SediMorph sediment transport and seabed morphology model (BAW 2005; Weilbeer 2005), as a fully-coupled hydrodynamic-wave-sediment transport model that spans all of the bay and the Delta. This model has been used in studies of sediment transport that support the San Francisco Bay Regional Dredged Material Management Program (MacWilliams et al. 2012b; Bever and MacWilliams 2013, 2014; Bever et al. 2014) and for the Prospect Island Tidal Habitat Restoration Project (DMA 2014a).

SUNTANS

SUNTANS (Stanford Unstructured Nonhydrostatic Terrain following Adaptive Navier–Stokes Simulator) is an open-source 3-D circulation model developed at Stanford University that computes flows on an unstructured grid using a finite-volume method (Fringer et al. 2006; Wang et al. 2009; Wolfram et al. 2016). SUNTANS is highly parallelized and designed to be used on large parallel computing

clusters. At its heart, SUNTANS is similar to the 3-D unstructured-grid UnTRIM model (Casulli and Walters 2000; Casulli and Stelling 2010), and uses two key approaches developed by Casulli (1990, 1999): (1) a semi-implicit free surface; and (2) a fractional step method to efficiently calculate the effects of non-hydrostatic pressures such as might be important at channel junctions or in channel bends. It includes algorithms for sediment transport and, through coupling with the SWAN model (Booij et al. 1999), surface wave effects on bottom stresses and flows (Chou et al. 2015). Various grids have been created for parts and the entirety of the Bay–Delta in the context of applications to the South Bay Salt Pond restoration (Hsu et al. 2013) as well as for detailed flow modeling in the Delta (Wolfram et al. 2016).

SCHISM

SCHISM (Semi-Implicit Cross-Scale Hydroscience Integrated System Model) is an open source semi-implicit model (Zhang et al. 2015, 2016) most recently extended from the Semi-implicit Eulerian–Lagrangian finite-element (SELFE) model (Zhang and Baptista 2008) and now an open source project led by the Virginia Institute of Marine Science (VIMS). SCHISM is semi-implicit in time, solving the Reynolds-averaged hydrostatic primitive equations using several of the same strategies as UnTRIM and SUNTANS. However, SCHISM treats a number of the steps in a novel way, by combining mass and momentum analytically (rather than algebraically) and in discretizing the resulting equation using finite elements. As a result, SCHISM is able to use a terrain-conforming vertical gridding system and more relaxed horizontal gridding constraints, which can be beneficial in channels with complex bathymetry. The SCHISM suite includes coupling to a wind-wave model, 3-D sediment, 2-D morphology, and several nutrient models. Only the nutrient model has been applied in the Bay–Delta.

The Bay–Delta SCHISM project is an application of 3-D SCHISM that allows cross-scale, multi-dimensional flow and transport in the Bay–Delta to be studied (Ateljevich et al. 2015). Although in the public version of the model the entire domain is represented in 3-D, VIMS and DWR are on the verge of releasing a version with more flexible vertical coordinates (Zhang et al. 2015) that allow regionalized tuning of vertical resolution and selective use of 2-D. Bay–Delta SCHISM has been calibrated on flow, water surface elevation, salt, and temperature over the full Bay–Delta (Ateljevich et al. 2015) and on nutrients for the Bay as part of the Salmon Ecosystem Simulation and Management Evaluation (SESAME) project. The application is currently being adapted by the National Oceanic and Atmospheric Administration (NOAA) as the standard for datum conversions as part of the VDatum (vertical data transformation software) program. CDWR has applied SCHISM to a variety of drought-related problems, including tidal effects, visualization and quantification of mixing processes for salt, circulation in Franks Tract, and near-field velocity resulting from the installation of drought barriers, which is discussed in more detail below. The base model resolution was chosen to resolve horizontal variation of primary velocity realistically along the larger channels in the bay and Delta; the model can run at speeds of 0.25 to 0.5 years per day of computation for a 2009 salinity and temperature benchmark on clusters at CDWR (typically 128 cores per simulation) and VIMS (typically 144 cores per simulation). Although the use of high performance computing can be difficult for non-institutional users, one advantage of a parallel computational approach to nutrient problems is that the transformation calculations involve little interprocess communication and scale efficiently.

RMA2

RMA has developed a series of finite element models for 1-D, 2-D, and 3-D simulation of flow, salinity, water quality, and sediment transport in streams and estuaries. The RMA Bay–Delta model of the bay and Delta is a coupled 1-D and 2-D model that uses RMA2 and RMA11 computational engines. The model domain extends either from Martinez through the Delta or from the Golden Gate through the Delta, with the bay, western Delta, and Franks Tract portions represented in 2-D, and the remaining channels of the Delta represented in 1-D. The RMA Bay–Delta model has been calibrated and applied in many previous studies such as the Flooded Islands Pre-Feasibility Study (RMA 2005), the Delta Risk Management Strategy project (URS Corporation

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

2011), and the Prospect Island Tidal Restoration study (RMA 2012). RMA has also more recently developed a 3-D model of the pre-development estuary using UnTRIM (RMA 2015; Andrews et al., submitted).

Delft3D

UNESCO–IHE (Institute for Water Education), Deltares, and the USGS (U.S. Geological Survey) have developed the Bay–Delta model within the Computational Assessments for Requirements fo Change for the Delta Ecosystem (CASCaDE) II project, applying the Deltares Delft3D-FM (flexible mesh) software. Delft3D-FM is an unstructured version of Delft3D, a widely-used hydrodynamic modeling software suite developed by Deltares of the Netherlands. Delft3D-FM, in contrast to Delft3D, utilizes a finite-volume, unstructured grid framework, allowing for variable resolution in regions of complex topography and bathymetry, and in regions where forcing functions and responses change rapidly (Kernkamp et al. 2011). The unstructured grid framework allows for polygon-shaped grid cells of arbitrary degree in 2-D (latitude and longitude) space, and includes 1-D channel networks. Model capabilities include 3-D salinity and temperature transport and dynamics, an atmospheric heat flux model driven by spatial fields of relative humidity, air temperature, and cloudiness for water temperature dynamics, dynamic wind-wave coupling, and formulations for sediment transport and morphodynamics.

Delft3D-FM has been applied to the San Francisco Bay–Delta region for the evolution of hydrodynamics, salinity, and temperature dynamics. This model is applied as part of the USGS-led CASCaDE II project that applies a linked modeling approach to provide scientific basis for regional policy decisions about water supply and Bay–Delta ecosystem health. The Delft3D-FM model domain includes the Pacific Ocean north to Point Reyes; the south, central and north San Francisco bays, the lower Yolo floodplain up to Fremont Weir; numerous channels of the north, central and south Delta; and the flooded islands of Franks Tract and Mildred Island. Links have been created with Deltares-developed sediment (Achete et al. 2015), phytoplankton, and habitat suitability models, in which spatial and temporal maps of hydrodynamics serve as the primary driver of the other models. This linked model approach has been successfully applied in a proof-of-concept framework to generate spatial habitat maps for key Bay-Delta species, including *Corbicula fluminea* and Delta Smelt (*Hypomesus transpacificus*). Related to this work, Knowles and Lucas (2015) describe the initial development of a new phytoplankton model that provides a new tool to explore links between physical and ecological processes in the Bay–Delta. We expect that this model and the work done through the CASCaDE project will be applied in the future for many of the types of applications we describe in later sections.

Other Multi-Dimensional Models

Additional 2-D and 3-D models have been applied to simulate parts of the estuary, including Si3D (Semi-implicit 3D), Mike-21, FVCOM (Finite Volume Coastal Ocean Model), and EFDC (Environmental Fluid Dynamics Code). The Si3D model was developed by the USGS (see Smith 1997) for application to the Delta and has been applied to look at dissolved oxygen dynamics in the Stockton Deepwater Ship Channel (DWSC) (Doyle et al. 2008; Monismith et al. 2008). Since 2014, FVCOM has been applied as part of the San Francisco Bay Operational Forecast System to provide nowcast and forecast guidance of water levels, currents, water temperature, and salinity in the bay and at its entrance (Peng et al. 2014; NOAA 2016). However, the FVCOM model extends into only a small portion of the western Delta, so it is not discussed in detail. Other multi-dimensional model applications have focused largely on salt transport in the bay (Gross et al. 2009; Chua and Fringer 2011), the effects of sea level rise in the bay (Holleman and Stacey 2014), and sediment dynamics in the bay (Ganju and Schoellhamer 2009; van der Wegen and Jaffe 2013) without resolving the Delta. The applications discussed below will focus specifically on multi-dimensional modeling in the Delta, primarily with a view towards consequences of habitat and flows for the transport of biota in and through the Delta.

MULTI-DIMENSIONAL MODELING APPLICATIONS

As seen in Table 1, 2-D and 3-D models both represent many of the physical processes that drive flow and transport processes in the Delta. The following two sections highlight recent studies that have investigated the ability of 2-D and 3-D models to represent specific processes.

Modeling Junction Dynamics in 1-D, 2-D, and 3-D

A key aspect of transport and dispersion in the Delta appears to be the dispersive effect of flows through the many junctions of the Delta. Analyzing temperature dynamics in the Stockton DWSC, Monismith et al. (2009) found that the dispersive flux of heat from the San Joaquin side of the Delta into the Bay required effective dispersion coefficients of ca. $1000\,m^2\,s^{-1}$ whereas dispersion in the DWSC itself was ca. $30\,m^2\,s^{-1}$ (c.f. Schmieder et al. 2008). Monismith et al. (2009) argued that the nominal mechanism for this behavior was chaotic dispersion: dispersion associated with flow splits at the junctions.

Computations made using the particle-tracking model STARWalker (Stanford Three-dimensional Augmented Random Walker) reported in Sridharan (2015) show the importance of flow behavior at junctions. STARWalker uses flows computed by DSM2. The CDWR Java Particle-Tracking Model (JPTM) used with DSM2 (e.g., see Kimmerer and Nobriga 2008) essentially assumes complete mixing at junctions. In contrast, STARWalker can be run with either complete mixing at junctions or by allowing particles to follow streamlines that are computed using a highly idealized potential flow model of each junction in DSM2.

The way junction conditions (complete mixing vs. streamline following) influence particle dispersion and paths through the Delta was evaluated by Sridharan (2015), who found significant differences in spatial distributions of particles released at various source locations, such as Rio Vista, depending on the junction model. In particular, Sridharan (2015) found that there were large differences in the timing and rates of particle arrival at the export pumps between model runs that used complete mixing and model runs that used streamline following. This is an important practical metric of model performance. A particularly striking example of this difference was found for a model of Delta Smelt salvage during the spring of 2000, with the STARWalker's salvage prediction being significantly better ($r^2 = 0.48$) with streamline following than with complete mixing at junctions ($r^2 = 0.01$). We note that 3-D particle tracking simulations based on UnTRIM and the Flexible Integration of Staggered-grid Hydrodynamics Particle-Tracking Model (FISH-PTM) simulations reported by Gross et al. (2010) appear to agree even better with salvage observations.

Thus, proper description of flows at junctions may be important to predicting the transport pathways of any quantity, e.g., larval fish, through the Delta. Observations of flows in the Georgiana Slough/Mokelumne River junction reported in Gleichauf et al. (2014) show the complexity of these flows, which can include separation behavior that was well represented by a highly resolved 3-D SUNTANS model of the region (see Schoellhamer et al. 2016). Beyond showing fidelity to observations, these model results also revealed a reach–scale feature of the flow not readily observable by fixed instrumentation or limited transecting: the creation of interspersed patches of fluid from different sources as a result of the phasing of flows that enter and leave the junction as acted on by lateral mixing in the junction (Figure 2). This nicely illustrates that multi-dimensional modeling, beyond its utility at addressing straightforward engineering questions, can also provide important new conceptual insights about physical processes in the Bay–Delta.

There are, necessarily, trade-offs between model resolution and model scale, raising the question of what level of detail is necessary and sufficient to properly model junction effects on system level dispersion. Wolfram et al. (2016) examined this issue through a series of model studies of the Georgiana Slough/Mokelumne River junction. The most detailed computation used very high resolution (an average of 3-m horizontal and 0.8-m vertical) and included the effects of non-hydrostatic pressures—a level of detail that would be difficult to replicate at the scale of the whole Bay–Delta and for seasonal time scales if computed on a desktop workstation. Based on comparison to observations, this model run (the "base case") was taken to represent actual conditions. Other

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

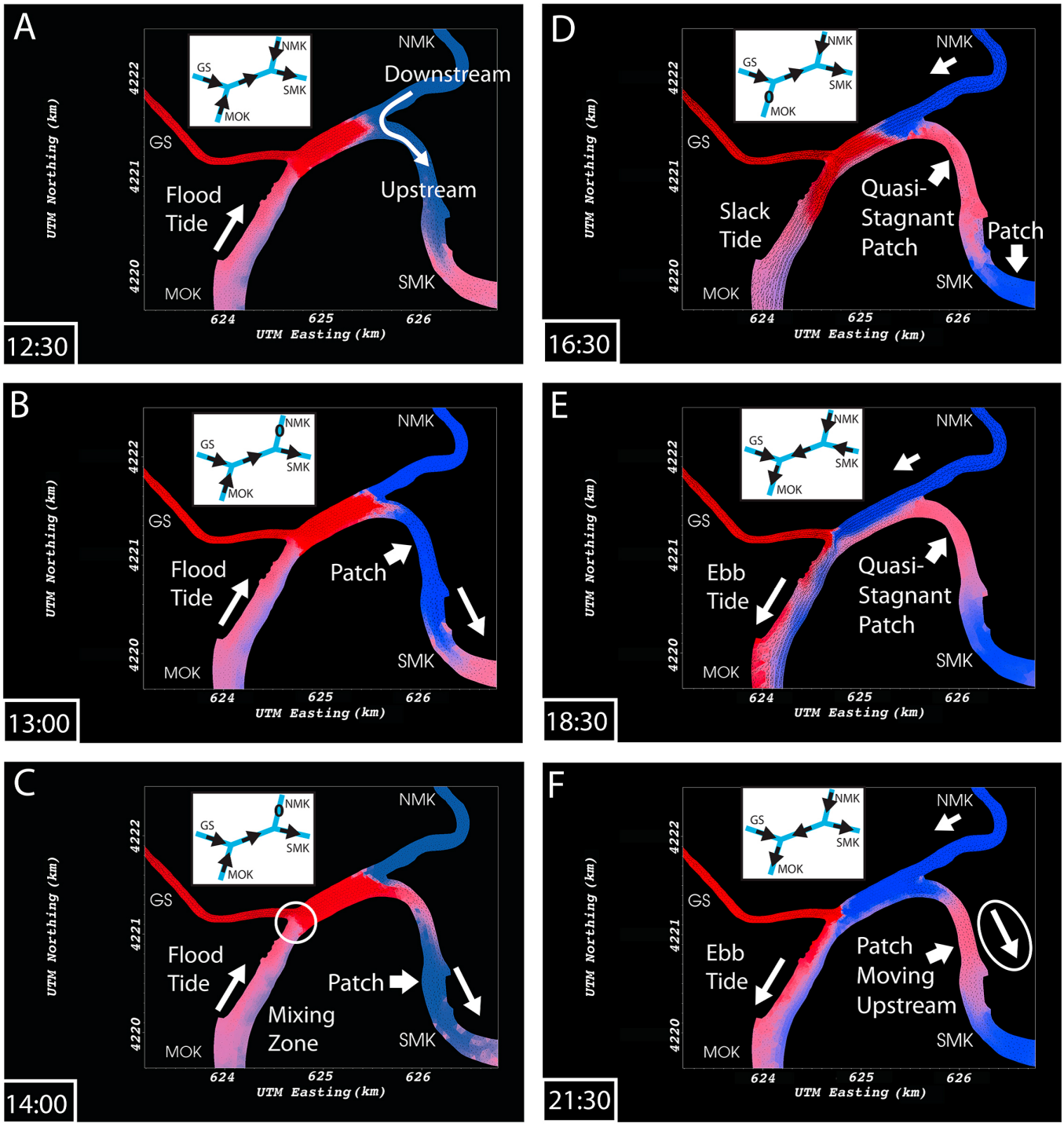

Figure 2 SUNTANS simulation for June 1, 2012, at: (A) 12:30; (B) 13:00; (C) 14:00; (D) 16:30; (E) 18:30; and (F) 21:30. Red signifies water that originally came from Georgiana Slough (GS) and blue represents water coming from the north Mokelumne (NMK). The insets show the mean flow in each branch of the junction during the simulation. Source: Gleichauf et al. (2014).

model runs included a 3-D run with coarser resolution (6-m horizontal) and hydrostatic pressures and a 2-D run with the same resolution as the coarse 3-D run. To assess how well the models handled mixing at the junction, for each model run Wolfram et al. (2016) computed the fraction of fluid from each of the four sources in the four receiving channels, and compared the results to the base case. The case of complete mixing—i.e., what is used in standard DSM2-PTM modeling (e.g., Kimmerer and Nobriga 2008)—can be computed analytically and so it was not necessary to make separate DSM2-PTM runs for this case. Based on computed correlation between the results of the various model runs and the base case, Wolfram et al. (2016) found that: (1) the lower-resolution, hydrostatic 3-D case provided nearly the same result as did the base case (r^2=0.98/0.99 with the DCC open/closed); (2) the 2-D run was nearly as good as the 3-D run (r^2=0.94/0.95); and (3) the complete mixing model was somewhat less accurate (r^2=0.61/0.71). In examining the different models, Wolfram et al. (2016) concluded that the tidal timescale details have less effect on mixing by the junctions than do the bulk features of the flow and differences in sub-tidal flow structure (in this case caused by operation of the DCC). As a consequence, simplified models like the DSM2-PTM provide some ability to model Delta-scale dispersion, especially if streamline following is used at junctions. Nonetheless, the work of Wolfram et al. (2016) suggest that substantial improvement in fidelity of the results can be obtained using 2-D models, although the extra computational effort of high resolution 3-D models may not provide much improvement beyond that of 2-D models in some applications. This demonstrates that for modeling some processes that can be adequately represented in 2-D (Table 1), a 3-D model may not be necessary. However, physical processes that are themselves inherently 3-D—e.g., stratified flows associated with salinity gradients in Suisun Bay and the western Delta, or temperature stratification in the DWSC—require 3-D modeling (Table 1).

An interesting application of STARWalker described in Sridharan (2015) was its use to identify specific flow paths through the Delta. Although a high percentage of particles released at Rio Vista followed a direct path south from the Sacramento River near the DCC, many particles followed a path in which particles travelled farther downstream and entered the interior Delta through either Threemile Slough or through the confluence of the Sacramento and San Joaquin rivers. Moreover, by examining which paths were important for certain given conditions (e.g., Export : Inflow ratios, gate operations, and barriers), this type of analysis could be used to design operational strategies to reduce entrainment at the export pumps. Although this example draws on the use of a well-established 1-D model, it illustrates what *could* be done quite profitably with the flow fields and particle tracks derived from multi-dimensional models, likely with more certainty since the representation of the physical system is more accurate when all spatial variations are accounted for explicitly.

High Resolution Modeling of Secondary Circulation

Numerical simulations of circulation and residence time in Clifton Court Forebay (CCF) by MacWilliams and Gross (2013) provide an interesting example of a relatively simple problem, where the flow dynamics are inherently 3-D. Clifton Court Forebay (CCF) is a regulating reservoir in the southern Delta that is used to improve operations of the California State Water Project (SWP) Harvey O. Banks Pumping Plant and water diversions to the California Aqueduct (Clark et al. 2009). Inflows to CCF are controlled by five radial gates, and outflows from CCF include water exports from the Banks Pumping Plant to the SWP and from CCF to the Byron Bethany Irrigation District. The purpose of these simulations was to provide a better understanding of circulation patterns, flow pathways, and residence time in the CCF to support ongoing studies of pre-screen loss and fish facility efficiency for Delta Smelt at the SWP export facilities. During windy periods, the flow within the CCF is highly 3-D, with strong wind-driven surface velocities driving a counterclockwise subsurface gyre (Figure 3). During periods of high winds, this gyre in CCF resulted in significant mixing, and increased the range of estimated transit times from the radial gates to the Banks Pumping Plant. The vertical variability of wind-driven velocities also resulted in mixing that was manifested by a large range of estimated residence times for high-wind conditions. In contrast, during higher-export and low-wind conditions, residence times were much shorter, and

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

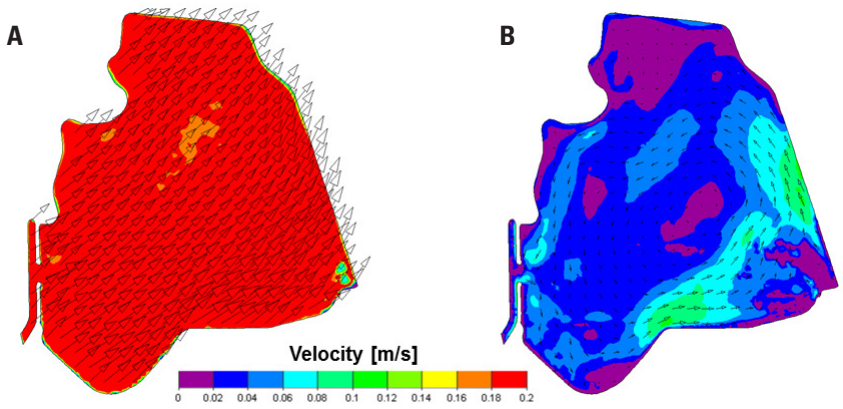

Figure 3 Predicted (A) surface and (B) subsurface circulation patterns in CCF on June 25, 2008, at 00:00 PST, during a period with relatively high winds, when the radial gates were closed and the Banks Pumping Plant was not operating. Source: MacWilliams and Gross (2013).

increased with distance from the Banks Pumping Plant. This example demonstrates that, particularly under windy conditions, a 2-D model of CCF would produce significantly different circulation patterns and residence times than a 3-D model. Even though wind effects can generally be represented by a 2-D model (Table 1), in some cases wind can have a strong influence on 3-D processes that cannot be represented using a 2-D model.

USING MODELS TO UNDERSTAND OBSERVATIONAL DATA

Because models can give us much greater spatial and temporal data resolution than we can get from monitoring at a limited number of times and stations, models can enhance our understanding of both physical and biological monitoring data. This section presents two examples that highlight how combining modeling with observational data can help to improve our understanding of the observations.

What We Have Learned from Models about the X2 Data Sets

Abundance or survival of several estuarine species have historically been positively related to freshwater flow, as indexed by the position of the daily-averaged 2-psu isohaline near the bed, or X2 (Jassby et al. 1995; Kimmerer et al. 2009, 2013). As noted in the State of Bay–Delta Science 2008, X2 is used in managing flow into the estuary, and is considered a measure of the physical response of the estuary to changes in freshwater flow (Kimmerer 2002). In most applications, X2 is estimated using either autoregressive equations (Jassby et al. 1995; Monismith et al. 2002; Gross et al. 2009; MacWilliams et al. 2015) or surface salinity from a small set of fixed observation stations that are typically near shore (CDEC 2016). As MacWilliams et al. (2015) discussed, there are limitations to both approaches, particularly for low and high values of X2, and models have been instrumental both in increasing our understanding of the relationship between X2 and flow and in improving these calculations.

One application of a 3-D circulation model to the Bay–Delta is the study of unsteady salinity intrusion in northern San Francisco Bay, i.e., X2 variability with flow, reported in MacWilliams et al. (2015). In this case, MacWilliams et al. (2015) used the model results to develop an improved auto-regressive model, like that described in Jassby et al. (1995), suitable for use in planning. The value of modeling in this case is two-fold: (1) whereas low-flow values of outflow have high uncertainty, the model calculates X2 variability for specified (hence known) flows, and thus, the 3-D model (and possibly the new autoregressive equation) provides the ability to invert measured salinities at low flow to compute outflow; and (2) computed salinity fields for very high flows provide for accurate determination of X2 at high flow for cases where the existing salinity monitoring

network has only coarse resolution or during periods when X2 is downstream of all the salinity stations. Moreover, since high flows are rare, the model can be used to represent conditions that are rarely observed.

Two interesting implications of the MacWilliams et al. (2015) autoregressive model are that: (1) the time constant of adjustment to flow changes is large when flow is small and small when flow is large—behavior that Denton (1993) also incorporated into his so-called G model; and (2) the steady-state response to flow is such that $X2 \sim Q^{-1/5}$ whereas Monismith et al. (2002) found that $X2 \sim Q^{-1/7}$ based on surface salinity measurements described in Jassby et al. (1995) and USGS Polaris transect data. It is not clear at this time which power law is correct. Monismith (submitted) developed a time series model based on simplified dynamics—including $X2 \sim Q^{-1/6}$—that appears to be as accurate as that of MacWilliams et al. (2015); accordingly, differences in power law behavior may not be of much practical purpose. A potentially more substantive concern with 3-D model results for high flows is that the highly stratified conditions that exist at high flows are difficult to model accurately. Numerical diffusion associated with computing vertical momentum and salt transport and also with horizontal transport of salt can weaken the net salt transport associated with gravitational circulation (Chua and Fringer 2011). This weakening of salt transport would tend to increase the sensitivity of modeled X2 to flow.

Using Models to Investigate Fish Survey Data Sets

Another example of how hydrodynamic models have been used to increase our understanding of long-term data sets is the quantitative analysis conducted by Bever et al. (2016) to combine long-term fish sampling data from the estuary with detailed 3-D hydrodynamic modeling to investigate the relationship between historic fish catch and hydrodynamic complexity. In their analysis, the Fall Midwater Trawl (FMWT) Delta Smelt catch data from 1967 to 2012 were used to rank stations based on their relative historic Delta Smelt catch (Figure 4A). Thirty-five metrics of environmental complexity were developed from the FMWT observations and a set of simulations from the UnTRIM Bay–Delta model. Bever et al. (2016) then evaluated the correlations between historic Delta Smelt catch and 35 quantitative metrics of environmental complexity at each station to determine which variables were most highly correlated to historic Delta Smelt catch. The three metrics found to be most predictive of historic Delta Smelt catch were the percent of the time salinity was less than 6 psu, the maximum depth-averaged current speed, and the Secchi depth at each FMWT station in the vicinity of Suisun Bay.

Using these three quantitative metrics of environmental complexity derived from observed data and 3-D model predictions (Bever et al. 2016), the relative ranking of stations for Delta Smelt catch in Suisun Bay across 4 decades could be predicted. It was also possible to develop a 2-D map of the historic habitat index based on these three metrics (Figure 4B), and to evaluate how these conditions varied during different years (see Bever et al. 2016). This analysis revealed that a key to historic Delta Smelt catch is the overlap of low salinity, low maximum velocity, and low Secchi depth regions. The predictions of the hydrodynamics from the 3-D numerical model were integral in further understanding spatial variability in the fish catch on scales smaller than the estuary-wide salinity gradient. These results also demonstrated that hindcasts from multi-dimensional models can be combined with long-term data sets to explore environmental conditions at different spatial and temporal scales in order to improve the understanding of observed biological data. Although Bever et al. (2016) focused only on the relationship between hydrodynamic complexity and Delta Smelt in the estuary, the methods they developed could be extended to other species and areas of interest in the estuary.

USING MODELS TO UNDERSTAND CIRCULATION AND WATER SUPPLY

Evaluating the Effect of the Emergency Drought Barriers

Bay–Delta SCHISM was introduced in 2014–2015 during an extreme drought, so many CDWR applications of SCHISM have been associated with the effects of the emergency drought barrier at West False River (CDWR, forthcoming). For salinity, SCHISM was first deployed as an expository tool, producing animations to demonstrate the tidal

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

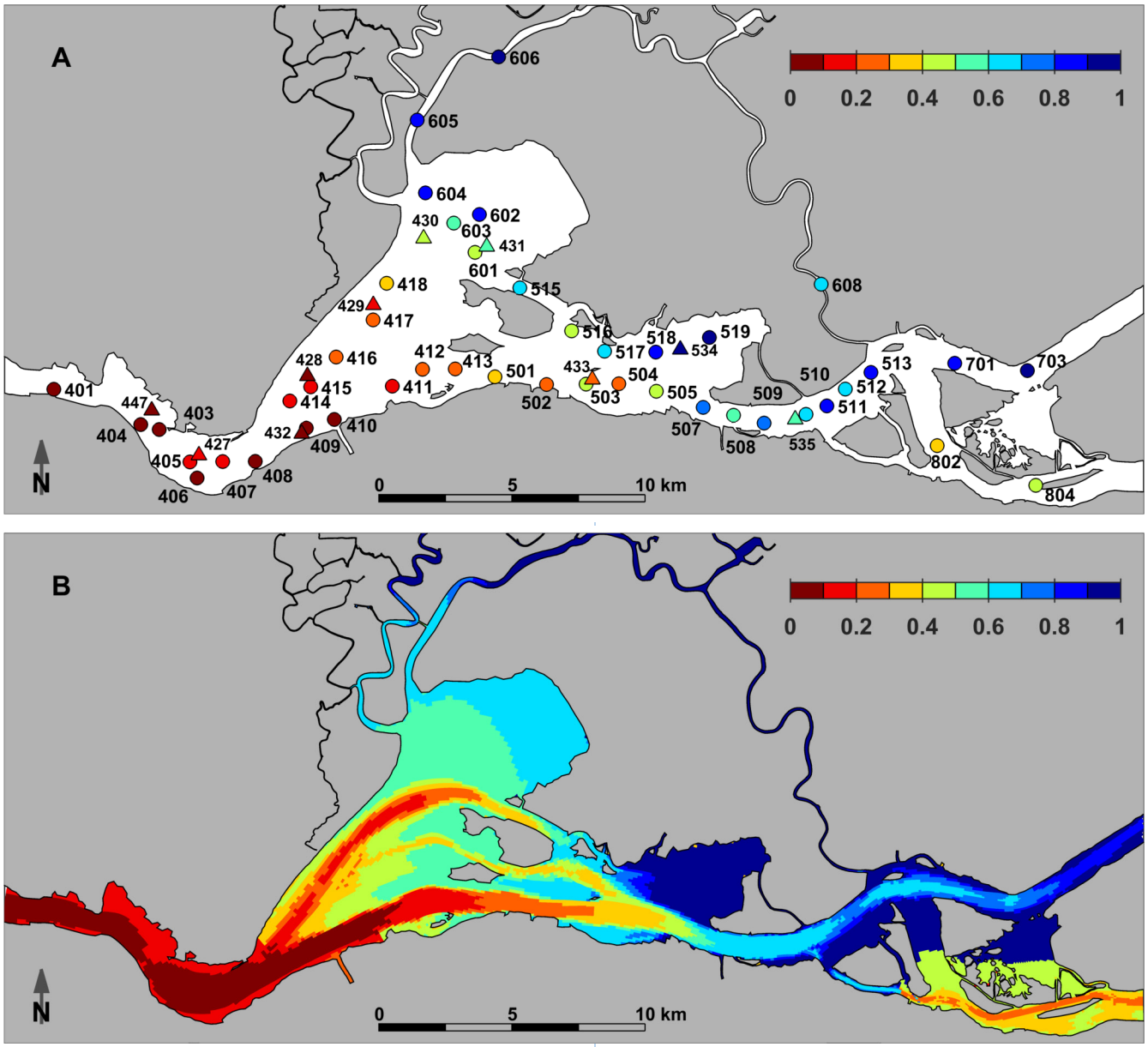

Figure 4 (**A**) FMWT (circles) and Bay Study (triangle) stations in Suisun Bay, colored based on relative station ranking based on historic Delta Smelt catch; (**B**) Two-dimensional maps of the station index for Delta Smelt based on the salinity, velocity, and Secchi depth metrics. Modified from Bever et al. (2016).

pumping salinity intrusion mechanism that motivated the West False River barrier design (Figure 5). SCHISM was recalibrated for extreme low flow in 2014, achieving agreement with data collected in 2013–2015, and was used together with the 1-D DSM2 model for some operational forecasts and retrospectives. The SCHISM model was not used to study expected barrier performance in 2015 because the screening methodology for selecting locations and benefits of the barrier focused on the water cost of compliance with State Water Board Decision D-1641 water quality objectives, an iterative optimal control problem that required thousands of rapid trial evaluations, and DSM2, with a run speed of 80,000 times real time, served this purpose better.

Over 2015, SCHISM evolved into the main tool used to answer velocity and circulation questions

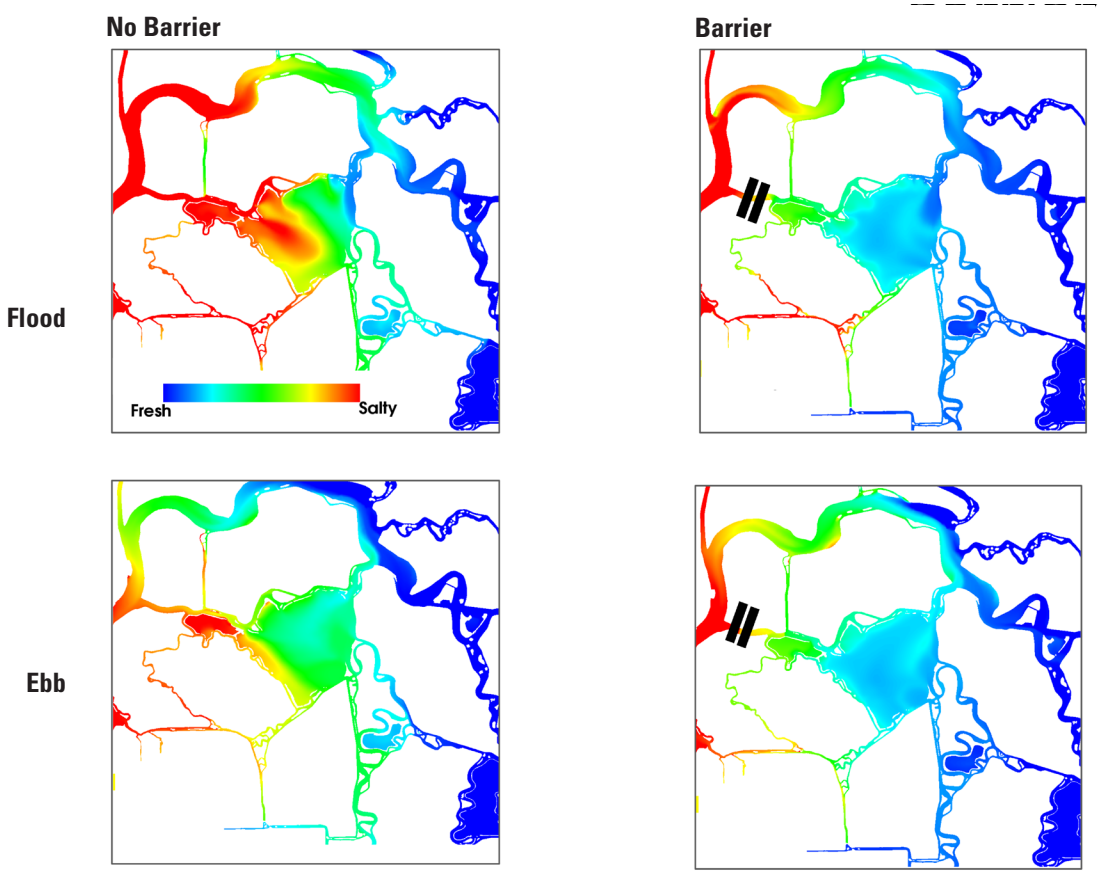

Figure 5 Illustration of the effect of the Emergency Drought Barrier on tidal pumping, as presented to the State Water Resources Control Board

associated with the emergency drought barrier and to vet sites for scour monitoring. SCHISM predicted changes to tidal range and flow patterns accurately enough to identify errant flow stations and ultimately was able to describe global circulation changes in salinity—the dominant water supply question.

A related issue concerned circulation changes in Franks Tract. One hypothesis was that the barrier would cause pockets of very long residence time to develop behind the barrier relative to ambient waters and lead to significant algal blooms—which ultimately were not observed. Initial modeling by CDWR with SCHISM indicated that a wide low velocity gyre could form in the eastern portion of Franks Tract, stimulated by amplified oblique inflow from Old River down remnant north–south pathways, and that this recurrent circulation pattern could offset the increase in residence time and induce more mixing. At the same time, it was noted that this was a fragile flow structure that could be suppressed by wind and macrophyte vegetation, and the specifics (speed of wind, prevalence of pondweed) would not be known until later. As a result of the perceived sensitivity of the result, a water quality site in Franks Tract near the Old River inlet was set up so CDWR could monitor it continuously, ultimately confirming relatively low transverse mixing between the eastern remnant channels and Franks Tract. The model, data, and associated discussion in Delta Science Program workshops contributed to an improved reconstruction of Franks Tract dynamics and how to focus future monitoring.

Using Models to Evaluate the Effects of Sea Level Rise

A particularly valuable aspect of models is their ability to forecast conditions that have yet to occur. Some of the first applications of 3-D models in the Bay–Delta focused primarily on salt intrusion,

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

and comprised valuable tools to investigate how sea level rise and levee failures in the Delta could influence water quality (MacWilliams and Gross 2007; MacWilliams and Gross 2010). MacWilliams and Gross (2010) evaluated salinity intrusion over one annual hydrologic cycle under five levels of sea level rise between 15 cm and 140 cm based on Delta outflows and operations as they were during 2002. Their model predicted that these increases in sea level would result in an increase in X2 throughout the year (Figure 6A), with predicted median increases ranging from 0.7 km for the 15-cm sea level rise scenario to more than 7 km for the 140-cm sea level rise scenario. However, the increase in X2 was highest during the transient conditions that occurred during larger outflow events, and the maximum X2 increases predicted for each rate of sea level rise over the 1-year period were between 60% and 120% higher than the predicted median increases (Figure 6B).

Chua and Xu (2014) used SUNTANS to look at the effect of sea level rise on salinity intrusion, finding that at moderate steady-state flows (300 m^3 s^{-1}), a 1.5-m sea level rise would result in a 10 km increase in X2 relative to present conditions. At higher steady-state flows (2000 m^3 s^{-1}), the effect was less pronounced, with a similar sea level rise producing only a 4 km increase in X2. This suggests that the transient and steady-state influence of sea level rise on X2 may be different. Also using SUNTANS, Holleman and Stacey (2014) explored how shoreline condition—i.e., levees at present shore locations as opposed to tidal flooding of existing low-elevation regions around the Bay such as the marshes of San Pablo and Suisun bays—affected tidal dynamics. They found that "preserving original shorelines, produces

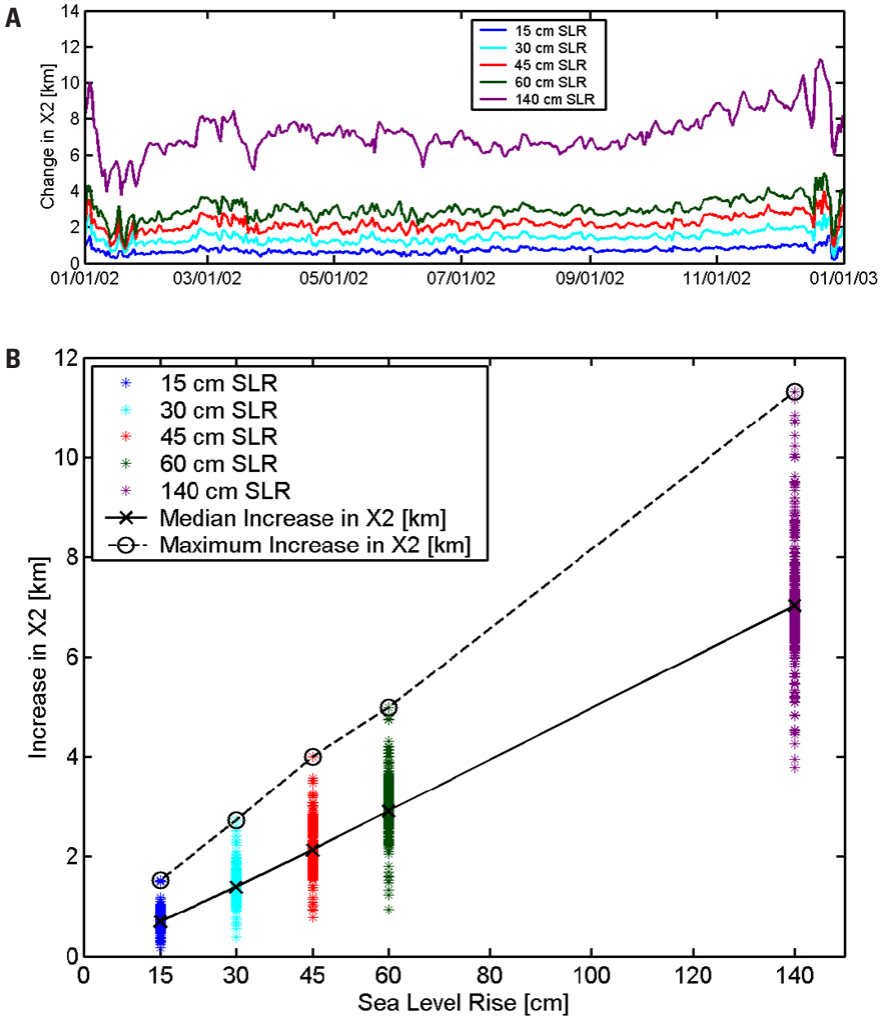

Figure 6 (**A**) Predicted change in X2 relative to Baseline scenario for 15-cm SLR scenario, 30-cm SLR scenario, 45-cm SLR scenario, 60-cm SLR scenario, and 140-cm SLR scenario; (**B**) Scatter plot of the predicted increase in X2 for each day during 2002 for each of the sea level rise scenarios; solid black line shows the median increase in X2 for each SLR scenario and the dashed black line shows the maximum increase in X2 for each SLR scenario. Modified from MacWilliams and Gross (2010).

additional tidal amplification" whereas allowing for the "flooding of adjacent low-lying areas introduces frictional, inter-tidal regions that serve as energy sinks for the incident tidal wave." When sea level rise is combined with tidal amplification, the predicted increase in X2 is higher than when tides are not amplified (Figure 6A). The overall result is that sea level rise can significantly alter tidal dynamics as well as increasing salinity intrusion. Thus, these modeling studies suggest that any evaluation of large-scale Delta restoration or modification should include sea level rise modeling (see also the NRC 2014 report on Everglades restoration).

USING MODELS TO UNDERSTAND PHYSICAL HABITAT

Using Models to Evaluate Historic Habitat

Although models are commonly used to forecast conditions that have yet to occur, a recent application of the UnTRIM model by RMA demonstrates the utility of using models to hindcast historic conditions for which very limited observation data are available (RMA 2015; Andrews et al., submitted). Anthropogenic changes to the estuary over the past 2 centuries have altered both the hydrology and the geometry of the estuary (Andrews et al., submitted). To examine how these changes have altered physical habitat in the estuary, 3-D hydrodynamic models were constructed to study the system in its "pre-development" condition (before

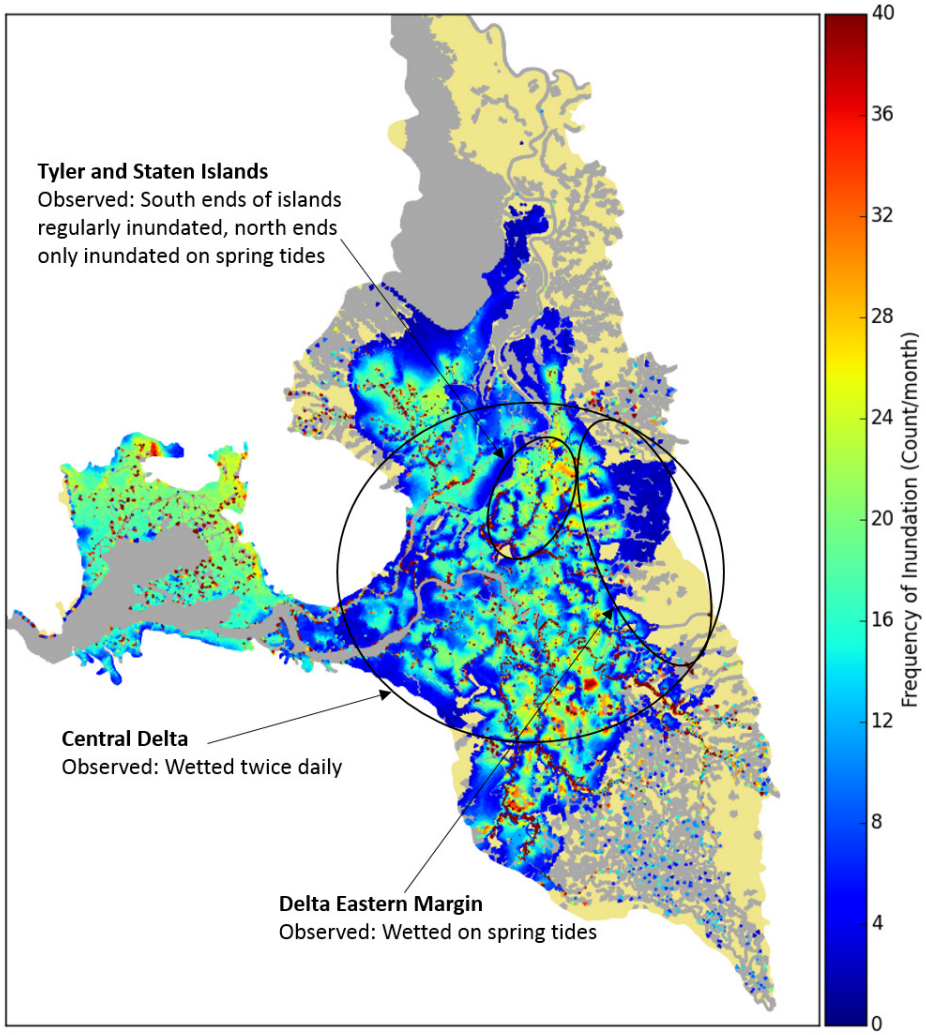

Figure 7 Inundation frequency in the pre-development upper San Francisco Estuary (source: Andrews et al., submitted). Historical observations are given along with the general area where the observation was made. The corresponding modeled values are the median of monthly inundation frequencies for months with maximum net estuary outflow less than 1000 $m^3 s^{-1}$. Areas which remain dry are shown as beige. Areas which remain wet are shown as gray.

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

significant modern anthropogenic influence) and in its contemporary condition. The pre-development system model was created to match the pre-development channel configuration in the upper estuary by the San Francisco Estuary Institute (Whipple et al. 2012), and calibrated by varying the marsh plain elevations to match sparse observed data points of tidal characteristics. These tidal characteristics included tidal range in channels and marsh plain inundation depth and frequency (Figure 7), as well as broader metrics, such as the extent of freshwater tidal habitat.

Through comparison of the pre-development and contemporary models, Andrews et al. (submitted) evaluated how changes to both the hydrology and the geometry of the estuary have affected salinity. Their results show that salt intrusion in the pre-development system was found to be slightly more sensitive to outflow and responded faster to changes in outflow than in the contemporary system. Changes in estuary hydrology were responsible for more of the salt intrusion differences between the two systems than were changes in estuary geometry and bathymetry. For example, for the same inflows, their results indicated that the X2 position in the pre-development and contemporary systems would be located within 5 km of each other 90% of the time (RMA 2015). However, when differences in both net outflow and bathymetry between the contemporary and pre-development systems were considered, there were larger differences in both average and seasonal predictions of low salinity zone (LSZ) area and volume. On average, the model predicted a higher variation in LSZ volume, area, and average depths in the pre-development simulation (RMA 2015; Safran et al. 2016). These insights into how changes to the hydrology and geometry of the system have affected physical habitat, provide a valuable resource to guide future restoration efforts in the estuary.

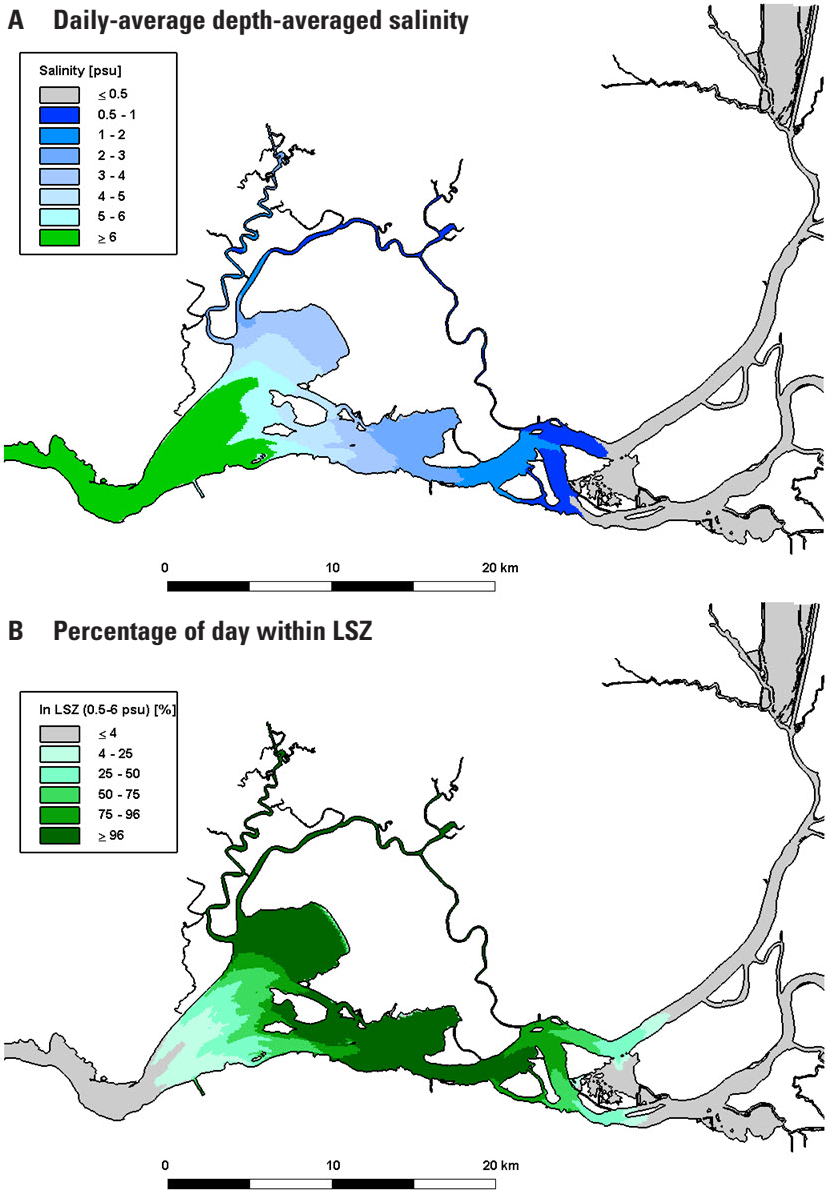

Figure 8 (**A**) Daily-averaged depth-averaged salinity between Carquinez Strait and the western Delta on a day when X2 is approximately 75 km; (**B**) percent of the same day that the depth-averaged salinity is within the low-salinity zone (between 0.5 and 6 psu). Source: MacWilliams et al. (2015).

Expanding our Perspective Beyond X2 to a Broader View of the Low Salinity Zone

Modeling has played an important role in broadening our perspective beyond a 1-D view of X2, to a better understanding of the position, area, and volume of the LSZ and how these variables relate to X2 (e.g., Kimmerer et al. 2013; MacWilliams et al. 2015). Detailed maps showing the location of the LSZ, and the tidal excursion of the LSZ over each day (Figure 8) have broadened the discussion beyond X2 to begin to focus on the range of X2 values that produce low salinity habitat in the areas of Honker Bay and Grizzly Bay (DMA 2014b; MacWilliams et al. 2015). This shift from a linear (X2) to a more geographic focus has also allowed us to broaden our focus from thinking only in terms of the LSZ, to better understanding the importance of overlapping regions of low salinity, high turbidity, and low velocity for producing conditions that have historically yielded the most consistent catch of species such as Delta Smelt (Bever et al. 2016).

Recent work by MacWilliams et al. (2016), demonstrates that multi-decadal 3-D simulations of the Bay–Delta are now computationally feasible. They used salinity predictions from a 35-year simulation to develop maps of salinity distribution over seven periods for six fish species, and combined the salinity distribution maps with historic fish-sampling data to allow for visualization of fish abundance and distribution. These maps can be used to explore how different species respond to annual differences in salinity distributions in the estuary and expand the understanding of the relationships among salinity and fish abundance, distribution, and population resiliency. Thus, models have played an important role in increasing our understanding of the mechanisms and processes that may be responsible for the correlations between X2 and fish abundance, and are suitable for future applications that inform and support a broader system-wide approach to understanding Delta ecology.

The Effect of Large-Scale Restoration in the Delta on Turbidity and Sediment Transport

The Prospect Island Tidal Habitat Restoration Project is a joint effort by the CDWR and the California Department of Fish and Wildlife (CDFW) to restore the 1,600 acres in Prospect Island to freshwater tidal wetland and open water (subtidal) habitats to benefit native fish and improve aquatic ecosystem functions (CDWR 2016b). The UnTRIM Bay–Delta model was applied with the SWAN wave model and the SediMorph morphologic model to evaluate potential effects of the Prospect Island Restoration Project on sediment transport and turbidity in the Sacramento DWSC and the Cache Slough complex (DMA 2014a). This approach allowed for a direct method to evaluate changes in sediment dynamics in the project vicinity, because sediment transport, deposition and re-suspension, the effect of wind waves, and the potential for deposition within Prospect Island to influence regional sediment dynamics were all explicitly simulated.

Baseline conditions and a range of restoration alternatives were compared to assess how different restoration design configurations affected hydrodynamics and turbidity during both summer conditions and during a “first flush” with high flow and high turbidity from the Sacramento River. These comparisons enabled specific alternatives to be identified that resulted in the smallest effects on the turbidity regime in the DWSC and the Cache Slough Complex where elevated turbidity provides an essential component of Delta Smelt habitat. In addition, model results also identified several important influences of the restoration on the turbidity regime that were not anticipated in advance. For example, under Baseline conditions during low outflow periods typical of late-summer and early-fall, turbidity tends to be relatively low in Miner Slough because of the downstream transport of low turbidity water from the Sacramento River. However, when the levee between Prospect Island and Miner Slough is breached, the model predicted that the tidal prism of Miner Slough significantly increases because of the filling and draining of Prospect Island each tidal cycle. This increased tidal prism draws turbidity from Cache Slough up Miner Slough on flood tide and results in an increase in turbidity from the mouth of Miner Slough to the breach location (Figure 9). This higher-turbidity corridor in lower Miner Slough, also leads to a small reduction in turbidity in both Cache Slough and the Sacramento DWSC. Over time, these turbidity dynamics are expected to evolve as

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

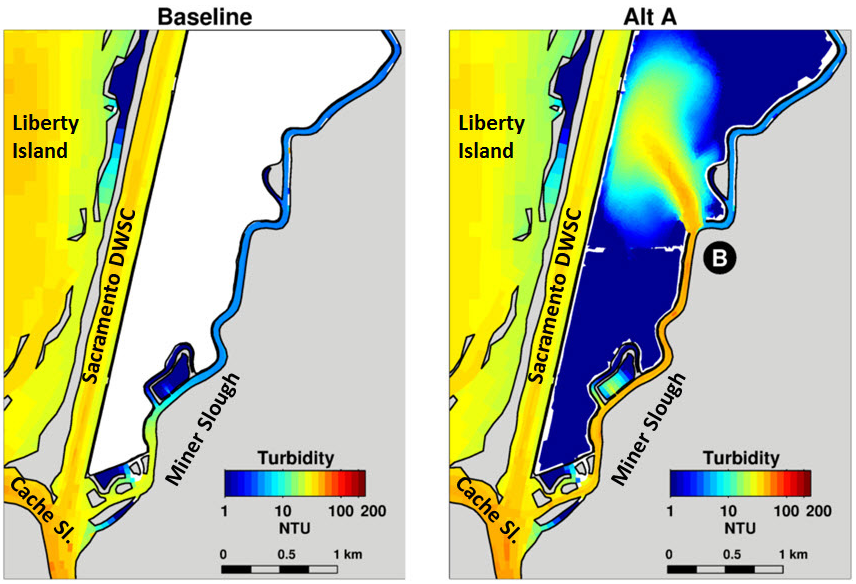

Figure 9 Predicted turbidity in the vicinity of Prospect Island under Baseline conditions and under restoration Alternative A (Alt A), with a single breach (B) between Miner Slough and Prospect Island. Source: Delta Modeling Associates (2014a).

deposition within Prospect Island and the evolution of shallow tidal wetlands reduces the tidal prism.

This application highlights that tidal restoration in the Delta can have regional influences on turbidity, and may also affect downstream sediment supply because of deposition that occurs within breached islands. A recent independent scientific review has also raised concerns that water diversions in the north Delta could "exacerbate the downstream sediment starvation that is already occurring" (Simenstad et al. 2016). Both tidal restoration in the Delta on a large scale and major changes to Delta operations could have a large influence on the sediment transport regime in the Delta. These changes and how they are implemented could influence the rate of sediment accumulation within restored Delta islands, have regional effects on Delta turbidity, and affect the downstream sediment supply to the bay. Modeling of these changes using available 3-D hydrodynamic, wind wave, and sediment transport models can be used to evaluate future changes to the Delta system, and to develop alternatives that will achieve the greatest possible benefits for water supply and habitat restoration while minimizing adverse effects on the sediment supply to downstream areas in the system.

USING MODELS TO UNDERSTAND FISH BEHAVIOR AND MOVEMENT

One of the most powerful applications of multi-dimensional modeling is to use models to examine links between organism behavior and flow (see Cowen et al. 2007). One classic example of these links is that of "selective tidal stream transport" (STST): the net horizontal transport of weakly swimming organisms by exploitation of vertically sheared tidal flows. Effectively, by changing vertical position at appropriate tidal phases, organisms, such as copepods or larval fish, can move large distances each tidal cycle or maintain a geographic position despite water movement. For example, using 3-D modeling, Simons et al. (2006) showed how various zooplankton could maintain particular positions in the LSZ of the St. Lawrence Estuary (see also North et al. 2008). Tracking individual "particles" with behavior moved by flow has also been used to assess connectivity of different regions in space, e.g., different coral reefs in the Caribbean (Cowen et al. 2000) and regions of the California coast (Simons et al. 2013).

More generally, beyond including the effects of hydrodynamic transport on populations made up of particles (individual organisms) moving through the model domain, so called individually based models (IBMs) can also incorporate physiology, growth, reproduction, etc. (e.g., Rose et al. 2013). However, there is the substantial challenge of knowing the behavior to be used in the model. For example, depending on which of the bioenergetically possible swimming behaviors Mysid shrimp used in the St. Lawrence Estuary, Simons et al. (2006) found that there could be either upstream migration from the LSZ to Montreal, maintenance of position in the LSZ, or downstream migration into the Atlantic Ocean. Nonetheless, as suggested by Banas et al. (2009) in the context of modeling nutrient-phytoplankton dynamics in the Washington Shelf–Salish Sea region, this form of coupled modeling may also offer researchers the ability to invert observed data on the distribution of organisms to infer behavior.

As implemented in 3-D models discussed below, particle tracking of organisms has three components: (1) transport in three dimensions by computed (or assumed) currents; (2) mixing by turbulence via a random walk formulation, something that depends on the turbulence closure used; and (3) swimming/sinking/rising prescribed by the modeler. One particular advantage of particle tracking is that it is essentially error-free for advection, in contrast with numerical representations of scalar advection that always involve artificial diffusion and other undesirable aspects (Gross et al. 1999). We note that although particle tracking is conceptually simple, its implementation can be challenging (e.g., see Edwards et al. 2000), requiring care with how particle movements are treated near boundaries (Gross et al. 2010) and with ensuring that the random number generator used in the random walk step is truly random (Hunter et al. 1993).

Using Particle-Tracking Models to Understand Larval Retention

The work of Kimmerer et al. (2014) demonstrates the value of coupled observations and modeling. In several field studies carried out in Suisun Bay, Kimmerer and colleagues (Kimmerer et al. 1998, 2002) had attempted to find evidence of STST in larval fish and zooplankton distributions. Kimmerer et al. (1998) found that 2-D Eulerian calculations based on observations showed that the sampled organisms should have been swept out to sea by the observed net, subtidal flow, whereas in reality, they were able to remain in Suisun Bay.

Using hydrodynamic model output from the UnTRIM Bay–Delta model (MacWilliams et al. 2015) with the particle-tracking code FISH-PTM (Gross et al. 2010), Kimmerer et al. (2014) explored the effects of swimming behavior on the fate of particles that were initially located in Suisun Bay and the western Delta. In their study, they were able to examine how particle fate varied with both hydrology (wet or dry years) and behavior. Echoing the results of the study of the St. Lawrence Estuary by Simons et al. (2006), both pure downwards swimming (i.e., sinking) and tidally varying upwards and downwards swimming increased retention of particles in Suisun Bay at all flows (Figure 10). Notably one of the behavioral patterns—upwards swimming at 0.25 mm s^{-1} and downwards swimming at 0.75 mm s^{-1} (their "Tidal 0.5" behavior)—produced distributions of particles in different salinity classes that matched with reasonable accuracy observed distributions of the copepod *Eurytemora affinis*.

Beyond addressing the question posited by Kimmerer et al. (1998) of to what extent tidal correlations of organism position in the water column and flow are important to the retention of organisms in the estuary, additional features of the effects of combining swimming with complex 3-D transport emerged. Notably, Kimmerer et al. (2014) showed that much of the retention at low Delta outflows happened in the sloughs of Suisun Marsh. Finally, beyond showing that possible behaviors enhanced retention, the Kimmerer et al. (2014) study also showed clearly how testing hypotheses with coupled 3-D physics-behavior models often leads to new questions. For example, as Kimmerer et al. (2014) ask at the end of their paper: What cues trigger a given swimming behavior? What behaviors might zooplankton use to remain in the Bay–Delta when flows are high? In the long run, this interdisciplinary iteration among modeling, observations, and the development of new conceptual models may be key to understanding how and why various restoration and management actions succeed or fail.

Using Particle-Tracking Models to Estimate Fish Entrainment

Gross et al. (2010) developed the FISH-PTM to represent particle-transport processes. The model can be used to simulate both passive particles and particles with swimming behaviors. The FISH-PTM runs offline, using hydrodynamic model results saved from a 3-D model. This makes it possible to simulate a large number of particle-tracking scenarios and to evaluate different particle behaviors without re-running the hydrodynamic model.

Using hydrodynamic results from the UnTRIM Bay–Delta model (MacWilliams et al. 2015) and available observations, Gross et al. (2010) applied the FISH-PTM to estimate the hatching distribution of Delta Smelt in 1999 and 2007. The hatching distributions predicted for the 1999 conditions indicated hatching in areas that are consistent with current biological understanding based on recently conducted larval surveys. Gross et al. (2010) evaluated four

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

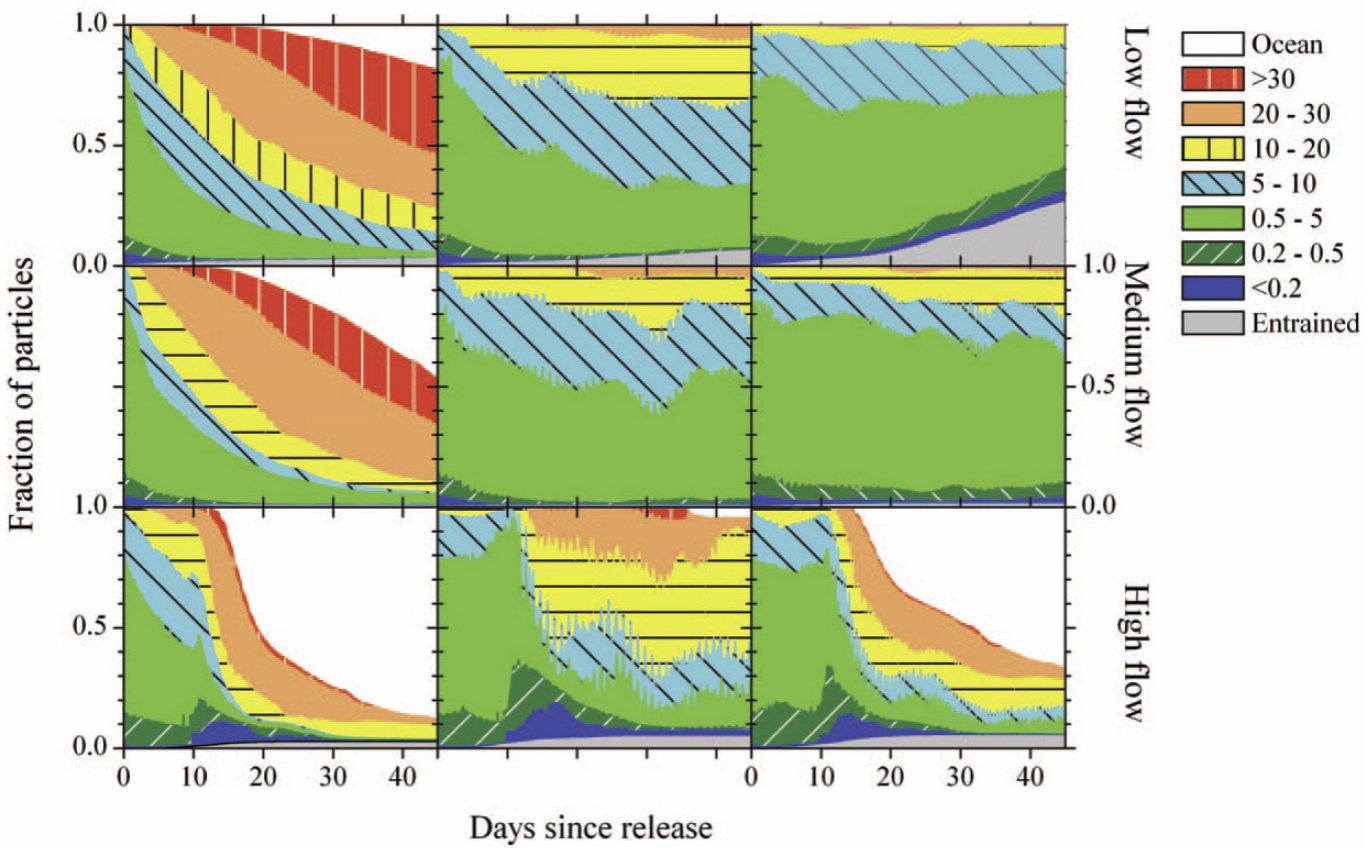

Figure 10 Particle fates for different flow rates and swimming behaviors as computed by Kimmerer et al. (2014). What is shown is the "fraction of the particles in several salinity bins, past the ocean boundary, or lost to entrainment in diversion flows from freshwater." Used with permission.

scenarios consisting of a passive scenario and three different upward swimming scenarios. The hatching distributions estimated for simulations with different hypothesized vertical migration behaviors were similar to the hatching distributions estimated for the passive particle-tracking scenario. The FISH-PTM simulation results indicated that, regardless of behavior, the fate of most of the larval and juvenile Delta Smelt was loss from natural mortality. The estimated entrainment losses for the different scenarios correspond to 2% to 3% of the total larval and juvenile fish that were estimated to hatch during 1999. The behaviors evaluated did not significantly influence the percent of the overall population of larval and juvenile Delta Smelt lost to export pumping. In all four scenarios, fewer than 20% of the fish hatched during 1999 were estimated to survive to the end of the simulation on July 21, 1999, corresponding to the end of the 20-mm survey period. Based on this, Gross et al. (2010) concluded that the vertical migration behaviors explored so far have limited influence on Delta Smelt distribution and fate.

The estimates of Delta Smelt distribution and, in particular, hatching distribution, are extremely relevant to ongoing policy decisions. Any project that modifies flow pathways and mixing in the Delta is likely to decrease entrainment of fish from some regions and increase entrainment of fish from other regions. Therefore, to confidently estimate the effects of such a project, it is critical to estimate the distribution of Delta Smelt and any other relevant fish species. Modeling tools and approaches such as those used by Gross et al. (2010) that coupled 3-D hydrodynamic modeling results with a properly validated PTM model–particularly if applied in a probabilistic framework–will be useful supplements to ongoing observational programs in estimating the distribution and entrainment of Delta Smelt and other

species for current conditions and different Delta operations scenarios.

Linking Hydrodynamics with Nutrients and Fish

As part of the ongoing SESAME project (SFSU Romberg Tiburon Center, NASA, NOAA–NMFS), the biogeochemical model Carbon, Silicate, and Nitrogen Ecosystem (CoSINE) (Chai et al. 2002, 2003; Xiu and Chai 2014) was coupled to SCHISM and the Bay–Delta application, and tailored to handle domain-specific questions. The SESAME model is a full life-cycle bioenergetic model of salmon that covers riverine, estuarine, and near-coast waters. The role of SCHISM is to model flow, food, and temperature in the estuary portion of the domain, which is applied in turn to individual salmon to evaluate the costs of migration through and rearing within the Bay–Delta. The model calibration is currently constrained to the bay and the lower Sacramento River; the application is in the process of extension to the full Bay–Delta, and, in the future, NOAA expects to combine SESAME with SCHISM's particle tracking to include the influence of detailed local velocity on migration and entrainment.

The SESAME approach to salmon modeling is individually based and uses particle modeling, but the emphasis of the ecosystem approach is on migration through a breadth of environments and life stages. Chinook Salmon spawn in rivers, and after a few months rearing in freshwater, juveniles migrate to the coastal ocean where food supplies and growth prospects are typically greater than in their natal river (Gross et al. 1988). The individual-based sub-model for juvenile salmon in SESAME includes a bioenergetics model to determine growth, and an area-restricted search algorithm to simulate foraging behavior. Domain-specific but coupled hydrodynamic and biogeochemistry models are used for the near coast (Regional Ocean Modeling System, ROMS), estuary (SCHISM) and upper Sacramento (River Assessment for Forecasting Temperature, RAFT).

DISCUSSION AND CONCLUSIONS

It is clear that multi-dimensional modeling of hydrodynamics in the Bay–Delta has advanced significantly in the last decade, to the point that it can now be used to accurately predict of flows both locally (e.g., in CCF) or at the scale of the whole Delta. The application of 3-D models of this type is the current state-of-the-art for modeling the Delta.

Multi-dimensional models have provided significant insights into some of the fundamental biological relationships that have shaped our thinking about the system, including exploring the relationships among X2, flow, fish abundance, and the LSZ. Through the coupling of multi-dimensional models with wind-wave and sediment-transport models, it has been possible to understand how large-scale changes to the system are likely to affect sediment dynamics, and to assess the potential effects on species that rely on turbidity for habitat. The coupling of multi-dimensional hydrodynamic models with particle-tracking models has led to advances in our thinking of the retention of food organisms in the estuary, the effect of south Delta exports on larval entrainment, and the pathways and behaviors of salmonids that travel through the Delta.

At present, we have succeeded in building models that are well-suited to engineering use. The models described above have been applied with success to answering specific questions about the Delta. These examples demonstrate that 3-D models in particular are now sufficiently well-developed that they should be the tool of choice for evaluating focused questions, particularly those involving purely hydrodynamic processes, such as the effects of sea level rise or large-scale restoration on salinity or sediment transport in the Delta. In more detailed studies, such as those involving secondary circulation or requiring resolution of vertical structure, resolved 3-D models are the only choice. In cases where 3-D models are harder to scale to longer times and broader spatial scales, the results of 3-D models may be harvested to inform coarser or simpler models (e.g., CDWR 2013, Section D8).

Lower-dimensional 1-D models will continue to be used in a variety of settings. Their simplicity and speed are valued in widespread deployment, and their empirical performance can be understood and be competitive over decades or centuries. Speed is important in algorithmic settings such as optimization and Bayesian analysis. Additionally, 3-D models may rely on forcing that is hard to predict

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

or flow features that are hard to simulate precisely, so that even where a complex process is known to be physically relevant it may not be represented well in a multi-dimensional model without sufficient resolution and data. For example, the importance of good bathymetry data for any application cannot be overstated. Even the best extant hydrodynamic model will not produce accurate flows if the bathymetric data is not accurate. In selecting a model for planning studies, dimensionality (Table 1), geographic and time scales, and the processes being simulated (Figure 1) must all be considered in any assessment of a model's predictive skill.

Through interdisciplinary work with biologists and ecologists, multi-dimensional models have enabled us to address key questions about the role of physical processes in shaping the ecology of the Bay–Delta (e.g., Lucas et al. 2002; Kimmerer et al. 2014; MacWilliams et al. 2016; Bever et al. 2016). In this realm, uncertainty in parameterizations of biological processes may be a much more significant limitation than uncertainty in computing transport and mixing. For example, 3-D models of the cyanobacterium *Microcystis* have been built (e.g., for the Swan River Estuary in western Australia [Robson and Hamilton 2004]), but they are seriously hampered by lack of knowledge about what factors influence *Microcystis* colony size, a critical determinant of the likelihood of bloom formation (2006 email conversation between S. Monismith and D. Hamilton, unreferenced, see "Notes"). In any modeling exercise it is important to recognize this fundamental challenge of understanding the critical uncertainties. At this point in time, it may be the case that improving biological and biogeochemical models is more important for improving Delta management than for improving multi-dimensional physical models. As one of us (SGM) was told in 1987 by the then-head of the IEP when he (SGM) began to get engaged in Bay–Delta science, "What is the use of a Rolls Royce understanding of the physics if all we have is a Yugo understanding of the biology?"[1]

Overall, what is most important is that the entire modeling exercise—i.e., choice of type of model, spatial discretization, the periods of simulation—be chosen properly to match the purpose of the model and the time-frame in which model results are required. At one end of the spectrum might be long-time-scale results that are required at relatively short notice. One very successful example of this type of modeling was the time series modeling (essentially a zero-dimensional model) done by Denton, Gartrell, and Sullivan at the Contra Costa Water District to examine the water supply implications of proposed X2 regulations then under development by the EPA. At the other end of the spectrum, one could imagine carrying out large-eddy simulation (LES) (c.f., Sotiropoulos 2015) to model the very detailed structure of flows at the proposed north Delta intakes. In this case, individual-based models of fish behavior (Goodwin et al. 2014) could be combined with high-resolution LES results to examine how interactions of flow and behavior would affect entrainment of out-migrating juvenile salmon. The fact that only relatively short periods of time (a few days) would need to be modeled makes this computationally feasible. Intermediate cases might include using 3-D modeling to predict in advance the effect on Delta salinities of the drought barrier installed in False River in 2015. In this case, the modeling that was required had to be reasonably accurate and delivered in a relatively short time, but the simulation period was a few months rather than decades (or days), again necessitating a compromise between computation scale and execution time.

The Future of Multi-Dimensional Modeling in the Delta

We anticipate that we will see continued improvements in model resolution and computational speed, at least in the application of multi-dimensional models using desktop computing and small clusters. In this regard, the needs of research intended to advance scientific understanding of the system may differ from what is needed in the near-term to address particular questions of system management (e.g., temporary barriers). In the former case, modeling should push the boundaries of what is possible; however, such studies are often undertaken with supporting field data collection and require either hydrodynamics, coupled physics, or forcing that may not extrapolate easily to planning scenarios. In the latter case, what is most important is to focus on what would provide the largest improvement in the fidelity of models used to make management and

1 Or something along those lines.

engineering decisions, and on identifying the types of multi-dimensional results that are accurate and robust for evaluating hypothetical scenarios. We believe both directions are important. Indeed, most of the examples described above would have been considered cutting-edge for environmental computations only a few years ago, whereas today, they should be considered to reflect appropriate engineering practice.

Several particular problems can and are being addressed now and in the near future with existing models:

1. **3-D structure and temporal variation of primary and secondary production as affected by in-Delta flows, gate and barrier operations, Delta outflow, and nutrient inputs.** The challenges here are to represent both the large effects of benthic grazing and zooplankton population dynamics adequately. Another possible direction for research would be to examine the competition between cyanobacteria like *Microcystis* that can form blooms when mixing is weak (Huisman et al. 2004) and diatoms for which strong mixing can offset sinking.
2. **Modeling temperature variability in time and in 3-D space.** Climate change will result in higher temperatures that will more frequently exceed lethal limits for Delta Smelt (Wagner et al. 2011). However, this conclusion is based on observations made largely with near-surface temperature sensors. Observations of temperature stratification in the DWSC reported in Monismith et al. (2008) suggest that near-bottom temperatures can be several degrees cooler than near surface temperatures during the day. Thus, deeper waters may offer Delta Smelt thermal refugia in the face of increasing surface temperatures. At present, our ability to model temperatures in general, and stratification in particular, is limited by lack of meteorological data for the Delta (2015 in-person conversation between S. Monismith and L. Herdman, unreferenced, see "Notes") and by limits to the predictability of turbidity and hence shortwave attenuation with depth. The development and calibration of a temperature model of the Delta is in progress as part of the CASCaDE project (Knowles and Lucas 2015), and future results from this work may provide further insights into how climate change will affect Delta water temperatures.
3. **Modeling wind and sea level effects on Delta outflow and hence salinities in northern San Francisco Bay and the western Delta.** Low-frequency variability in sea level in the Delta associated with both the coastal ocean sea level variability and with winds on Suisun Bay may explain flows associated with filling and emptying of the Delta observed by Oltmann (1998) that can be substantially larger at times than the corresponding outflow estimates from Dayflow (Monismith 2016). Although the sub-tidal hydrodynamic forcing that causes this variability is a complicated mixture of rectification of tidally varying bottom stresses and momentum advection (Smith and Cheng 1987; Monsen 2000), it can be directly addressed by 3-D modeling. We note that this may be challenging given that subtidal variability represents a small signal in the presence of large (tidal) variance (c.f. Sankaranarayanan and Fringer 2013), and there can be surprising subtleties with respect to averaging the effects of tidal variations in stratification on flow dynamics (Stacey et al 2010).
4. **Applying multi-dimensional models to understand the mechanisms behind the flow abundance relationships described by Jassby et al. (1995).** Initial applications by Kimmerer et al. (2009, 2013) explored hypotheses relating to the area and volume of the LSZ. However, more recent analyses by Bever et al. (2016) and MacWilliams et al. (2016) demonstrate the role that multi-dimensional models can play in understanding more broadly the combination of habitat characteristics that have led to historic abundance and distribution. These methods can be applied to other species and other portions of the bay and Delta to increase our understanding of habitat suitability for different fishes and life cycle phases.
5. **Applying coupled 3-D hydrodynamic, wave, and sediment models to investigate large-scale changes to the sediment dynamics of the system.** Observed long-term trends such as the clearing of the Bay (Schoellhamer 2011), system-wide changes to the

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

Delta resulting from large-scale restoration such as EcoRestore (CNRA 2016a), or changes to water conveyance such as WaterFix (CNRA 2016b) will affect sediment dynamics in the bay and Delta and subsequently influence species that are affected by turbidity. The example shown here for the Prospect Island Tidal Habitat Restoration Project (DMA 2014a) demonstrates that the tools to address and plan for these issues are already available.

6. **Develop coupled 3-D models of lower trophic levels.** This work has been started as part of the SCHISM work described above, and recommendations that prioritize species and processes have been developed as part of work panels and modeling white papers organized by the San Francisco Estuary Institute and Central Valley Regional Water Resources Control Board (Trowbridge et al. 2016).
7. **Support interdisciplinary work on coupled "fish and flows" modeling.** This has been accomplished in several recent studies described above (e.g., Bever et al. 2016; MacWilliams et al. 2016). Other examples where such collaboration has been formalized include the SESAME and NASA-HICO projects funded by NASA, which includes participants with local expertise in biogeochemistry but also borrows extensively from out-of-state experience in remote sensing and light transfer.
8. **Develop a 3-D operational Delta model that assimilates data in real time and issues and updates forecasts for flows, temperatures, and salinities.** We note that this is currently done for the California Current System by the set of West Coast Integrated Observing Systems (CeNCOOS [Central and Northern California, SCOOS [Southern California], etc.) and for San Francisco Bay (but not extending through the Delta) as part of the the San Francisco Bay Operational Forecast System (NOAA, 2016).

Final Comments

Although this paper focuses on modeling, it is clear that model utility is often limited by the availability of suitable data for boundary conditions (e.g., salinities and temperatures at open boundaries), forcing (e.g., winds), as well as observations to be used for calibration and verification of model output. Conversely, observations are necessarily limited in spatial detail and extent—something at which models excel. Thus, we believe that models and observations (at least those that go beyond monitoring) are most usefully done together, perhaps using models first to design the observational program and then using the resulting observations to confirm model results and to refine the model. At the same time, we acknowledge that this leads to a dichotomy of approach, one formulated to the cutting edge and guided by ample forcing and supporting data, and the other asked to give robust results over hypothetical planning scenarios fed by estimates.

Although the use of multi-dimensional models to advance system understanding is clearly valuable, it must be acknowledged that most (but not all) of the hydrodynamic modeling done to date has been intended to address very specific questions, i.e., as engineering studies of particular issues such as the effects of sea level rise, levee breaks, or temporary barriers on Delta salinities. Thus, we feel that there is much unexploited potential for using multi-dimensional models in interdisciplinary research like that described in Kimmerer et al. (2009) and Bever et al. (2016), which advance understanding of complex coupled physical–biological dynamics. As noted by Blumberg et al. (2010):

> "When not used to make specific engineering-type predictions, models can also be used to explore hypothesized linkages of forcing (e.g., flow) and responses (e.g., fish behavior, population dynamics, or water quality), suggesting relationships that can be explored through further analysis of data or by design of new data collection programs. Finally, models also can serve to link researchers from different disciplines, i.e. to provide a forum for interdisciplinary collaboration between [sic] fisheries biologists, social scientists and engineers."

With a view towards advancing multi-dimensional modeling of the Bay–Delta system in ways that will improve its utility to address regulation, management, and policy concerns, we echo the importance of the

recommendations made to the IEP as a result of a 2009 review of Bay–Delta modeling (Blumberg et al. 2010). Few will disagree that data and model integration and interdisciplinary collaboration on modeling and field research are essential steps for the future of Delta management. Yet, we can predict that it will continue to be difficult for disparate agencies, universities, and consultants to sustain collaborations beyond short funding cycles. Despite these challenges, significant advances have been made over the past decade in the development of application of multi-dimensional models. The numerous examples presented here represent the current state-of-the-science in Bay–Delta modeling, and indicate that we are continuing to make significant progress in using multi-dimensional models to interpret observational data, evaluate changes that affect circulation and water supply, advance our understanding of physical habitat, and test our hypotheses about fish behavior and movement.

In conclusion, modeling is an art that balances process resolution, computational speed, and accuracy. It is parsimonious with the data available to validate results and inferences. Modeling requires system knowledge and conceptual models to assess the time and space dimensions of the phenomenon or the objective being studied and in turn hones questions and approaches for modeling analysis. Multi-dimensional modeling provides the tools to move beyond the reductionist approach of trying to simplify the complexity of an entire system to a single variable such as X2, and instead focus on whole-system interactions. The challenge for the multi-dimensional modeler then becomes to take the enormous amount of information generated by the model and present it in a way that can be used to increase understanding of the system, without averaging out all of the important details. In this regard, the means of distilling the large amount of information into a meaningful result becomes one of the hallmarks of modeling success.

ACKNOWLEDGEMENTS

This paper was funded by the Delta Stewardship Council under the oversight of Darcy Austin. We would like to acknowledge the direction provided by the State of Bay–Delta Science Editorial Board in guiding the scope and content of this work. We would like to acknowledge Rose Martyr (USGS) and Lisa Lucas (USGS) for providing additional details regarding the Delft3D-FM implementation to San Francisco Bay as part of the CASCaDE project, and John DeGeorge (RMA) and Stephen Andrews (RMA) for assisting with the description of the RMA models and applications. SGM also acknowledges support of application of SUNTANS to the Bay–Delta provided by the Delta Stewardship Council Science Program. MLM would like to thank Erik Loboschefsky (CDWR) for his comments on the Prospect Island Tidal Habitat Restoration Project modeling example included here, and acknowledge the CDWR State Water Project, which funded this study. The authors gratefully acknowledge the thoughtful reviews provided by Oliver Fringer and one anonymous reviewer.

REFERENCES

Achete FM, van der Wegen M, Roelvink D, Jaffe B. 2015. A 2-D process-based model for suspended sediment dynamics: a first step towards ecological modeling. Hydrol Earth Syst Sci 19:2837–2857. doi: *http://dx.doi.org/10.5194/hess-19-2837-2015*

Andrews SW, Gross ES, Hutton PH. Modeling salt intrusion in the San Francisco Estuary prior to anthropogenic influence. *Continental Shelf Research*, submitted.

Ateljevich E, Nam K, Liu L, Saha S, Wang R, Zhang J. 2015. Bay–Delta SCHISM model developments and applications. In: Yu M, editor. Methodology for flow and salinity estimates in the Sacramento–San Joaquin Delta and Suisun Marsh. 36th annual progress report to the State Water Resources Control Board in accordance with water right decisions 1485 and 1641. California Department of Water Resources. p. 8-1 to 8-6. [accessed 2016 June 23]. Available from: *http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/AR2015/AR-2015-all.pdf*

Banas NS, Lessard EJ, Kudela RM, MacCready P, Peterson TD, Hickey BM, Frame E. 2009. Planktonic growth and grazing in the Columbia River plume region: a biophysical model study. J Geophys Res 114:C00B06. doi: *http://dx.doi.org/10.1029/2008JC004993*

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

[BAW] *Bundesanstalt für Wasserbau*. 2005. Mathematical module SediMorph. Validation document, version 1.1. Hamburg, Germany: The Federal Waterways Engineering and Research Institute. 77 p.

Bever AJ, MacWilliams ML. 2013. Simulating sediment transport processes in San Pablo Bay using coupled hydrodynamic, wave, and sediment transport models. Mar Geol 345:235–253. doi: *http://dx.doi.org/10.1016/j.margeo.2013.06.012*

Bever AJ, MacWilliams ML. 2014. South San Francisco bay sediment transport modeling. Prepared for U.S. Army Corps of Engineers, San Francisco District. 226 p.

Bever AJ, MacWilliams ML, Wu F, Andes L, Conner CS. 2014. Numerical modeling of sediment dispersal following dredged material placements to examine the possible augmentation of the sediment supply to marshes and mudflats, San Francisco Bay, USA. In: Proceedings of 33rd PIANC World Congress; 2014 June 1–5; San Francisco, CA. 18 p.

Bever AJ, MacWilliams ML, Herbold B, Brown LR, Feyrer FV. 2016. Linking hydrodynamic complexity to Delta Smelt (*Hypomesus transpacificus*) distribution in the San Francisco Estuary, USA. San Franc Estuary Watershed Sci 14(1). doi: *http://dx.doi.org/10.15447/sfews.2016v14iss1art3*

Blumberg A, Goodwin P, Houde H, Monismith S, Powell T, Simenstad S. 2010. Review of IEP and other Bay–Delta modeling focused on hydrodynamics and fish. [Internet]. [accessed 2016 June 23]. Available from: *http://www.water.ca.gov/iep/docs/IEPModelWorkshopReview.pdf*

Booij N, Ris RC, Holthuijsen LH. 1999. A third-generation wave model for coastal regions: 1. Model description and validation. J Geophys Res 104(C4):7649–7666. doi: *http://dx.doi.org/10.1029/98JC02622*

Burau JR, Monismith SG, Koseff J. 1993. Comparison of advective transport algorithms with an application in suisun bay, a sub-embayment of San Francisco Bay, California. In: Shen HW, Su ST, Feng W, editors. Hydraulic engineering. Proceedings of the American Society of Civil Engineers; 1993 July 25–30; San Francisco. New York: American Society of Civil Engineers. p. 1628–1634.

[CDEC] California Department of Water Resources, California Data Exchange Center. 2016. Daily X2 calculation [Internet]. [accessed 2016 Jan 15]. Available from: *http://cdec.water.ca.gov/cgi-progs/stationInfo?station_id=CX2*

[CDWR] California Department of Water Resources. 2009. Delta Risk Management Strategy: phase 1 risk analysis report. Section 11, salinity impacts. [Internet]. [accessed 2016 June 23]. Available from: *http://www.water.ca.gov/floodsafe/fessro/levees/drms/phase1_information.cfm*

[CDWR] California Department of Water Resources. 2013. Bay–Delta Conservation Plan draft EIR/EIS, Appendix 5A. [Internet]. [accessed 2016 June 23]. Available from: *http://baydeltaconservationplan.com/2015PublicReview/PublicReviewRDEIRSDEIS/PublicReviewRDEIRSDEIS_Links.aspx*

[CDWR] California Department of Water Resources. 2016a. Biological assessment for the California WaterFix. [Internet]. [accessed 2016 June 23]. Available from: *http://cms.capitoltechsolutions.com/ClientData/CaliforniaWaterFix/uploads/FIX_BA_TOC_V6.pdf*

[CDWR] California Department of Water Resources. 2016b. Prospect Island Tidal Habitat Restoration Project [Internet]. [accessed 2016 June 23]. Available from: *http://www.water.ca.gov/environmentalservices/frpa_prospect_restoration.cfm*

[CDWR] California Department of Water Resources. Forthcoming. Efficacy of 2015 West False River Emergency Drought Barrier.

[CWC] California Water Commission. 2016. Water Storage Investment Program draft technical reference. [accessed 2016 June 23]. Available from: *https://cwc.ca.gov/Documents/2016/WSIP/WSIP_Draft_TechRefDoc_Compiled.pdf*

[CNRA] California Natural Resources Agency. 2016a. California EcoRestore [Internet]. [accessed 2016 June 24]. Available from: *http://resources.ca.gov/ecorestore/*

[CNRA] California Natural Resources Agency. 2016b. California WaterFix [Internet]. [accessed 24 June 2016]. Available from: *http://www.californiawaterfix.com/*

Casulli V. 1990. Semi-implicit finite difference methods for the two-dimensional shallow water equations. J Comput Phys 86:56–74. doi: *http://dx.doi.org/10.1016/0021-9991(90)90091-E*

Casulli V. 1999. A semi-implicit numerical method for non-hydrostatic free-surface flows on unstructured grid. In: Numerical modelling of hydrodynamic systems. Proceedings of ESF Workshop NMHS; 1999 Jun 21–24; Zaragoza, Spain. Zaragoza: University of Zaragoza. p. 175–193.

Casulli V. 2009. A high-resolution wetting and drying algorithm for free surface hydrodynamics. Int J Numer Meth Fl 60(4):391–408. doi: *http://dx.doi.org/10.1002/fld.1896*

Casulli V, Cattani E. 1994. Stability, accuracy and efficiency of a semi-implicit method for three-dimensional shallow water flow. Comput Math Appl 27(4):99–112. doi: *http://dx.doi.org/10.1016/0898-1221(94)90059-0*

Casulli V, Cheng RT. 1992. Semi-implicit finite difference methods for three-dimensional shallow water flow. Int J Numer Meth Fl 15:629–648. doi: *http://dx.doi.org/10.1002/fld.1650150602*

Casulli V, Walters RA. 2000. An unstructured, three-dimensional model based on the shallow water equations. Int J Numer Meth Fl 32:331–348. doi: *http://dx.doi.org/10.1002/(SICI)1097-0363(20000215)32:3<331::AID-FLD941>3.0.CO;2-C*

Casulli V, Stelling G. 2010. Semi-implicit subgrid modelling of three-dimensional free-surface flows. Int J Numer Meth Fl 67:441–449. doi: *http://dx.doi.org/10.1002/fld.2361*

Casulli V, Zanolli P. 2002. Semi-implicit numerical modelling of non-hydrostatic free surface flows for environmental problems. Math Comput Model 36:1131–1149. doi: *http://dx.doi.org/10.1016/S0895-7177(02)00264-9*

Casulli V, Zanolli P. 2005. High resolution methods for multidimensional advection diffusion problems in free-surface hydrodynamics. Ocean Model 10 (1–2):137–151. doi: *http://dx.doi.org/10.1016/j.ocemod.2004.06.007*

Chai F, Dugdale RC, Peng T–H, Wilkerson FP, Barber RT. 2002. One dimensional ecosystem model of the equatorial pacific upwelling system. Part I: model development and silicon and nitrogen cycle. Deep–Sea Res II 49(13–14):2713–2745. doi: *http://dx.doi.org/10.1016/S0967-0645(02)00055-3*

Chai F, Jiang M, Barber RT, Dugdale RC, Chao Y. 2003. Interdecadal variation of the transition zone chlorophyll front, a physical-biological model simulation between 1960 and 1990. J Oceanogr 59:461–475. doi: *http://dx.doi.org/10.1023/A:1025540632491*

Cheng RT, Casulli V, Gartner JW. 1993. Tidal, residual, intertidal mudflat (TRIM) model and its applications to San Francisco Bay, California. Estuar Coast Shelf Sci 36:235–280. doi: *http://dx.doi.org/10.1006/ecss.1993.1016*

Cheng RT, Smith RE. 1998. A nowcast model for tides and tidal currents in San Francisco Bay, California. In: Proceedings of the Marine Technology Society Ocean Community Conference. Baltimore (MD): Marine Technology Society. p. 537–543.

Chou Y–J, Holleman RC, Fringer OB, Stacey MT, Monismith SG, Koseff JR. 2015. Three-dimensional wave-coupled hydrodynamics modeling in South San Francisco Bay. Comput Geosci 85:10–21. doi: *http://dx.doi.org/10.1016/j.cageo.2015.08.010*

Chua VP, Fringer OB. 2011. Sensitivity analysis of three-dimensional salinity simulations in North San Francisco Bay using the unstructured-grid SUNTANS model. Ocean Model 39:332–350. doi: *http://dx.doi.org/10.1016/j.ocemod.2011.05.007*

Chua VP, Xu M. 2014. Impacts of sea-level rise on estuarine circulation: an idealized estuary and San Francisco Bay. J Mar Sys 139:58–67. doi: *http://dx.doi.org/10.1016/j.jmarsys.2014.05.012*

Clark KW, Bowen MD, Mayfield RB, Zehfuss KP, Taplin JD, Hanson CH. 2009. Quantification of pre-screen loss of juvenile steelhead in Clifton Court Forebay. Sacramento (CA): California Department of Water Resources. 139 p. Available from: *http://baydeltaoffice.water.ca.gov/ndelta/fishery/documents/2009_clark_et_al_quantification_of_steelhead_pre-screen_loss.pdf*

Cowen RK, Lwiza KMM, Sponaugle S, Paris C, Olson D. 2000. Connectivity of marine populations: open or closed? Science 287:857–859. doi: *http://dx.doi.org/10.1126/science.287.5454.857*

Cowen RK, Gawarkiewicz G, Pineda J, Thorrold SR, Werner FE. 2007. Population connectivity in marine systems: an overview. Oceanography 20(3):14–21. doi: *http://dx.doi.org/10.5670/oceanog.2007.26*

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

[DMA] Delta Modeling Associates, Inc. 2014a. Evaluation of effects of prospect island restoration on sediment transport and turbidity: Phase 2 alternatives, final report, Prospect Island Tidal Habitat Restoration Project. Prepared for California Department of Water Resources and Wetlands and Water Resources, Inc. 165 p.

[DMA] Delta Modeling Associates, Inc. 2014b. Low salinity flip book, version 2.0. December 31, 2014.

DeGeorge JF. 1996. A multi-dimensional finite element transport model utilizing a characteristic-galerkin algorithm [dissertation]. [Davis (CA)]: University of California, Davis.

Denton RA. 1993. Accounting for antecedent conditions in seawater intrusion modeling–applications for the San Francisco Bay–Delta. In: Shen HW, Su ST, Feng W, editors. Hydraulic engineering. Proceedings of the American Society of Civil Engineers; 1993 July 25–30; San Francisco. New York (NY): American Society of Civil Engineers. p. 448–453.

Doyle L, Fleenor W, Schladow SG, Monismith S, Hench J, Smith P, Rueda F. 2008. An application of the SI3DWQ hydrodynamics and water quality model to the Stockton Deep Water Ship Channel. Prepared for the CALFED Ecosystem Restoration Program. 56 p.

Draper A, Munévar A, Arora S, Reyes E, Parker N, Chung F, Peterson L. 2004. CalSim: generalized model for reservoir system analysis. J Water Resour Plan Manag 130:480–489. doi: *http://dx.doi.org/10.1061/(ASCE)0733-9496(2004)130:6(480)*

Edwards CA, Batchelder HP, Powell TM. 2000. Modeling microzooplankton and macrozooplankton dynamics within a coastal upwelling system. J Plankton Res 22:1619–1648. doi: *http://dx.doi.org/10.1093/plankt/22.9.1619*

Fischer H, List E, Koh R, Imerger J, Brooks N. 1979. Mixing in inland and coastal waters. San Diego (CA): Academic Press.

Fong D, Monismith S, Stacey M, Burau J. 2009. Turbulent stresses and secondary currents in a tidal-forced channel with significant curvature and asymmetric bed forms. J Hydraul Eng 135(3):198–208. doi: *http://dx.doi.org/10.1061/(ASCE)0733-9429(2009)135:3(198)*

Fringer OB, Gerritsen M, Street R. 2006. An unstructured grid, finite-volume, nonhydrostatic, parallel coastal ocean simulator. Ocean Model 14:139–173. doi: *http://dx.doi.org/doi:10.1016/j.ocemod.2006.03.006*

Ganju NK, Schoellhamer DH. 2009. Calibration of an estuarine sediment transport model to sediment fluxes as an intermediate step for simulation of geomorphic evolution. Cont Shelf Res 29:148–158. doi: *http://dx.doi.org/10.1016/j.csr.2007.09.005*

Gleichauf KT, Wolfram PJ, Monsen NE, Fringer OB, Monismith SG. 2014. Dispersion mechanisms of a tidal river junction in the Sacramento–San Joaquin Delta, California. San Franc Estuary Watershed Sci 12(4). doi: *http://dx.doi.org/10.15447/sfews.2014v12iss4art1*

Goodwin RA, Politano M, Garvin JW, Nestler JM, Hay D, Anderson JJ, Weber LJ, Dimperio E, Smith DL, Timko M. 2014. Fish navigation of large dams emerges from their modulation of flow field experience. Proc Nat Acad Sci 111(14):5277–5282. doi: *http://dx.doi.org/10.1073/pnas.1311874111*

Gross ES, Koseff JR, Monismith SG. 1999. Evaluation of advective schemes for estuarine salinity simulations. J Hydraul Eng 125(1):32–46. doi: *http://dx.doi.org/10.1061/(ASCE)0733-9429(1999)125:1(32)*

Gross ES, MacWilliams ML, Kimmerer WJ. 2009. Three-dimensional modeling of tidal hydrodynamics in the San Francisco Estuary. San Franc Estuary Watershed Sci 7(2). doi: *http://dx.doi.org/10.15447/sfews.2009v7iss2art2*

Gross ES, MacWilliams ML, Holleman CD, Hervier TA. 2010. POD 3-D tracking modeling study: particle tracking model testing and applications report. Prepared for Interagency Ecology Program.

Gross MR, Coleman RM, McDowall RM. 1988. Aquatic productivity and the evolution of diadromous fish migration. Science 239:1291–1293. doi: *http://dx.doi.org/10.1126/science.239.4845.1291*

Healey MC, Dettinger MD, Norgaard RB, editors. 2008a. The State of Bay Delta Science 2008. [Internet]. [accessed 2016 June 23]. Available from: *http://www.science.calwater.ca.gov/pdf/publications/sbds/sbds_2008_final_report_101508.pdf*

Healey M, Dettinger M, Culberson S, Bottorff L. 2008b. Chapter 6: water supply. In: Healey MC, Dettinger MD, Norgaard RB, editors. The State of Bay Delta Science [Internet]. [accessed 2016 June 23]. Available from: *http://www.science.calwater.ca.gov/pdf/publications/sbds/sbds_2008_final_report_101508.pdf*

Holleman RC, Stacey MT. 2014. Coupling of sea level rise, tidal amplification, and inundation. J Phys Oceanogr 44:1439–1454. doi: *http://dx.doi.org/10.1175/JPO-D-13-0214.1*

Hsu K, Stacey MT, Holleman RC. 2013. Exchange between an estuary and an intertidal marsh and slough. Estuaries Coasts 36:1137–1149. doi: *http://dx.doi.org/10.1007/s12237-013-9631-2*

Huisman J, Sharples J, Stroom JM, Visser PM, Kardinaal WEA, Verspagen JMH, Sommeijer B. 2004. Changes in turbulent mixing shift competition for light between phytoplankton species. Ecology 85:2960–2970. doi: *http://dx.doi.org/10.1890/03-0763*

Hunter JR, Craig PD, Phillips HE. 1993. On the use of random walk models with spatially variable diffusivity. J Comp Phys 106:366–376. doi: *http://dx.doi.org/10.1016/S0021-9991(83)71114-9*

Jassby AD, Kimmerer WJ, Monismith SG, Armor C, Cloern JE, Powell TM, Schubel JR, Vendlinski TJ. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecol Appl 5(1):272–289. doi: *http://dx.doi.org/10.2307/1942069*

Kernkamp HWJ, Van Dam A, Stelling GS, de Goede ED. 2011. Efficient scheme for the shallow water equations on unstructured grids with application to the Continental Shelf. Ocean Dyn 61:1175–1188. doi: *http://dx.doi.org/10.1007/s10236-011-0423-6*

Kimmerer WJ, Burau JR, Bennett WA. 1998. Tidally-oriented vertical migration and position maintenance of zooplankton in a temperate estuary. Limnol Oceanogr 43:1697–1709. doi: *http://dx.doi.org/10.4319/lo.1998.43.7.1697*

Kimmerer WJ, Bennett WA, Burau JR. 2002. Persistence of tidally-oriented vertical migration by zooplankton in a temperate estuary. Estuaries 25:359–371. doi: *http://dx.doi.org/10.1007/BF02695979*

Kimmerer WJ, Nobriga ML. 2008. Investigating particle transport and fate in the Sacramento–San joaquin delta using a particle tracking model. San Franc Estuary Watershed Sci 6(1). doi: *http://dx.doi.org/10.15447/sfews.2008v6iss1art4*

Kimmerer WJ, Gross ES, MacWilliams ML. 2009. Is the response of estuarine nekton to freshwater flow in the San Francisco estuary explained by variation in habitat volume? Estuaries Coasts 32:375–389. doi: *http://dx.doi.org/10.1007/s12237-008-9124-x*

Kimmerer WJ, MacWilliams ML, Gross ES. 2013. Variation of fish habitat and extent of the low-salinity zone with freshwater flow in the San Francisco Estuary. San Franc Estuary Watershed Sci 11(4). doi: *http://dx.doi.org/10.15447/sfews.2013v11iss4art1*

Kimmerer WJ, Gross ES, MacWilliams ML. 2014. Tidal migration and retention of estuarine zooplankton investigated using a particle-tracking model. Limnol Oceanogr 59:901–916. doi: *http://dx.doi.org/10.4319/lo.2014.59.3.0901*

Knowles N, Lucas L. 2015. CASCaDE II Project final report. Prepared for Delta Science Program. [Internet]. [accessed 2016 June 23]. Available from: *http://cascade.wr.usgs.gov/reports/C2_final_report/CASCaDE_2_Final_Report.pdf*

Lucas LV, Cloern JE, Thompson JK, Monsen NE. 2002. Functional variability of habitats within the Sacramento–San Joaquin Delta: restoration implications. Ecol Appl 12:1528–1547. doi: *http://dx.doi.org/10.1890/1051-0761(2002)012[1528:FVOHWT]2.0.CO;2*

MacWilliams ML, Cheng RT. 2007. Three-dimensional hydrodynamic modeling of San Pablo Bay on an unstructured grid. In: Proceedings of the 7th International Conference on Hydroscience and Engineering; 2006 September 10–13; Philadelphia. Philadelphia (PA): Drexel University. 16 p.

MacWilliams ML, Gross ES. 2007. UnTRIM San Francisco Bay–Delta Model calibration report, Delta Risk Management Study. Prepared for the California Department of Water Resources. 101 p.

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

MacWilliams ML, Gross ES, DeGeorge JF, Rachielle RR. 2007. Three-dimensional hydrodynamic modeling of the San Francisco Estuary on an unstructured grid, IAHR, 32nd Congress, Venice Italy, 2007 July 1-6. 11 p

MacWilliams ML, Gross ES. 2010. UnTRIM San Francisco Bay–Delta Model sea level rise scenario modeling report. Delta Conservation Plan. Prepared for Science Applications International Corporation and the California Department of Water Resources. 562 p.

MacWilliams ML, Gross ES. 2013. Hydrodynamic simulation of circulation and residence time in Clifton Court Forebay. San Franc Estuary Watershed Sci 11(2). doi: *http://dx.doi.org/10.15447/sfews.2013v11iss2art1*

MacWilliams ML, Salcedo FG, Gross ES. 2008. San Francisco Bay–Delta UnTRIM Model Calibration Report, POD 3-D Particle Tracking Modeling Study. Prepared for California Department of Water Resources. 344 p.

MacWilliams ML, Salcedo FG, Gross ES. 2009. San Francisco Bay–Delta UnTRIM Model Calibration Report, Sacramento and Stockton Deep Water Ship Channel 3-D Hydrodynamic and Salinity Modeling Study. Prepared for U.S. Army Corps of Engineers, San Francisco District. 574 p.

MacWilliams ML, Kilham NE, Bever AJ. 2012a. South San Francisco Bay Long Wave Modeling Report, South San Francisco Bay Shoreline Study. Prepared for U.S. Army Corps of Engineers, San Francisco District. 226 p.

MacWilliams ML, Bever AJ, Gross ES. 2012b. Three-dimensional Sediment Transport Modeling for San Francisco Bay RDMMP, San Francisco Bay Regional Dredged Material Management Plan. Prepared for U.S. Army Corps of Engineers, San Francisco District. 190 p.

MacWilliams ML, Sing PF, Wu F, Hedgecock N. 2014. Evaluation of the potential salinity impacts resulting from the deepening of the San Francisco Bay to Stockton Navigation Improvement Project. In: Proceedings of 33rd PIANC World Congress; 2014 June 1–5; San Francisco, CA. 13 p.

MacWilliams ML, Bever AJ, Gross ES, Ketefian GA, Kimmerer WJ. 2015. Three-dimensional modeling of hydrodynamics and salinity in the San Francisco estuary: an evaluation of model accuracy, X2, and the low salinity zone. San Franc Estuary Watershed Sci 13(1). doi: *http://dx.doi.org/10.15447/sfews.2015v13iss1art2*

MacWilliams ML, Bever AJ, Foresman F. 2016. 3-D simulations of the San Francisco Estuary with subgrid bathymetry to explore long-term trends in salinity distribution and fish abundance. San Franc Estuary Watershed Sci 14(2). doi: *http://dx.doi.org/10.15447/sfews.2016v14iss2art3*

Monismith SG, Kimmerer W, Burau JB, Stacey MT. 2002. Structure and flow-induced variability of the subtidal salinity field in northern San Francisco Bay. J Phys Oceanogr 32(11):3003–3019. doi: *hhttp://dx.doi.org/10.1175/1520-0485(2002)032<3003:SAFIVO>2.0.CO;2*

Monismith SG, Hench J, Smith P, Fleenor WE, Doyle L, Schladow SG. 2008. An application of the Si3D hydrodynamics model to the Stockton Deep Water Ship Channel: physics and model application. Final report for CALFED ERP-02-D-P51. 62 p.

Monismith SG, Hench JL, Fong DA, Nidzieko NJ, Fleenor WE, Doyle L, Schladow SG. 2009. Thermal variability in a tidal river. Estuaries Coasts 32:100–110. doi: *http://dx.doi.org/10.1007/s12237-008-9109-9*

Monismith SG. An integral model of unsteady salinity intrusion in estuaries. *Journal of Hydraulic Research*, submitted.

Monismith SG. 2016. A note on Delta outflow. San Franc Estuary and Watershed Sci 14(3). doi: *http://dx.doi.org/10.15447/sfews.2016v14iss3art3*

Monsen N. 2000. A study of sub-tidal transport in Suisun Bay and the Sacramento–San Joaquin Delta, California [dissertation]. [Stanford (CA)]: Stanford University.

Monsen N, Cloern J, Burau JB. 2007. Effects of flow diversion on water and habitat quality: Examples from California's highly manipulated Sacramento–San Joaquin Delta, San Franc Estuary and Watershed Sci 5(3). doi: *http://dx.doi.org/10.15447/sfews.2007v5iss5art2*

[NOAA] National Oceanic and Atmospheric Administration. 2016. San Francisco Bay operational forecast system. [Internet]. [accessed 2016 Oct 24]. Available from: *https://tidesandcurrents.noaa.gov/ofs/sfbofs/sfbofs.html*

[NRC] National Research Council. 2014. Progress toward restoring the Everglades: The Fifth Biennial Review, 2014. Washington, D.C.: The National Academies Press. 240 p.

North EW, Schlag Z, Hood RR, Li M, Zhong L, Gross T, Kennedy VS. 2008. Vertical swimming behavior influences the dispersal of simulated oyster larvae in a coupled particle-tracking and hydrodynamic model of Chesapeake Bay. Mar Ecol Prog Ser 359:99–115. doi: *http://dx.doi.org/10.3354/meps07317*

Oltmann RN. 1998. Indirect measurement of delta outflow using ultrasonic velocity meters and comparison with mass-balance calculated outflow. [Internet]. [accessed 2016 June 23]. Interagency Ecological Program Newsletter 11(1):5–8. Available from: *http://sfbay.wr.usgs.gov/watershed/delta_outflow/*

Peng M, Schmalz RA, Zhang A, Aikman F. 2014. Towards the Development of the National Ocean Service San Francisco Bay Operational Forecast System, J Mar Sci Eng 2014(2[1]):247–286. doi: *http://dx.doi.org/10.3390/jmse2010247*

[RMA] Resource Management Associates. 2005. Flooded Islands Pre-feasibility Study, RMA Delta Model Calibration Report. Prepared for California Dept. of Water Resources and California Bay–Delta Authority. 158 p.

[RMA] Resource Management Associates. 2012. Appendices B, D, F, I, J, K. In: Prospect Island tidal restoration: synthesis of Phase 1 screening-level modeling evaluation of conceptual restoration alternatives. Prepared for the California Dept. of Water Resources.

[RMA] Resource Management Associates. 2015. Hydrodynamic and salt transport modeling of the pre-development upper San Francisco Estuary. Phase 2 technical memorandum. Prepared for the Metropolitan Water District of Southern California.

Robson BJ, Hamilton DP. 2004. Three-dimensional modelling of a *Microcystis* bloom event in the Swan River estuary, western Australia. Ecol Model 174(1-2):203–222. doi: *http://dx.doi.org/10.1016/j.ecolmodel.2004.01.006*

Robinson TD, Eldred MS, Wilcox KE, Haimes R. 2008. Surrogate-based optimization using multifidelity models with variable parameterization and corrected space mapping. AIAA J 46 (11):2814–2822. doi: *http://dx.doi.org/10.2514/1.36043*

Rose KA, Kimmerer WJ, Edwards KP, Bennett WA. 2013. Individual-based modeling of Delta Smelt population dynamics in the upper San Francisco Estuary: I. Model description and baseline results. Trans Am Fish Soc 142:1238–1259. doi: *http://dx.doi.org/10.1080/00028487.2013.799518*

Safran SM, Grenier L, Grossinger R. 2016. Ecological implications of modeled hydrodynamic changes in the upper San Francisco Estuary. Phase 2 technical memorandum. SFEI Publication #786. [Internet]. [accessed 2016 June 23]. Prepared for the Metropolitan Water District of Southern California. Available from: *http://www.sfei.org/documents/ecological-implications-modeled-hydrodynamic-changes-upper-san-francisco-estuary-phase-ii*

Sankaranarayanan S, Fringer OB. 2013. Dynamics of barotropic low-frequency fluctuations in San Francisco Bay during upwelling. Cont Shelf Res 65:81–96. doi: *http://dx.doi.org/10.1016/j.csr.2013.06.006*

Schmieder PJ, Ho DT, Schlosser P, Clark JF, Schladow SG. 2008. An SF6 tracer study of the flow dynamics in the Stockton Deep Water Ship Channel: implications for dissolved oxygen dynamics. Estuaries Coasts 31:1038–1051. doi: *http://dx.doi.org/10.1007/s12237-008-9093-0*

Schoellhamer DH. 2011. Sudden clearing of estuarine waters upon crossing the threshold from transport to supply regulation of sediment transport as an erodible sediment pool is depleted: San Francisco Bay, 1999. Estuaries Coasts 34:885–899. doi: *http://dx.doi.org/10.1007/s12237-011-9382-x*

Schoellhamer DH, Wright SA, Monismith SG, Bergamaschi BA. 2016. Recent advances in understanding flow dynamics and transport of water-quality constituents in the Sacramento–San Joaquin River Delta, San Franc Estuary Watershed Sci 14(4). doi: *http://dx.doi.org/10.15447/sfews.2016v14iss4/art1*

Simenstad CS, Van Sickle J, Monsen N, Peebles E, Ruggerone GT, Gosnell H. 2016. Independent review panel report for the 2016 California WaterFix Aquatic Science peer review. [Internet.] [accessed 2016 June 23]. Sacramento (CA): Delta Science Program. 75 p. Available from: *http://www.westcoast.fisheries.noaa.gov/publications/Central_Valley/BDCP/ca_waterfix_aq_sci_review_report_final.pdf*

http://dx.doi.org/10.15447/sfews.2016v14iss4art2

Simons RD, Monismith SG, Johnson LE, Winkler G, Saucier FJ. 2006. Zooplankton Retention in the Estuarine Transition Zone of the St. Lawrence Estuary. Limnol Oceanogr 51(6):2621–2631. doi: *http://dx.doi.org/10.4319/lo.2006.51.6.2621*

Simons RD, Siegel DA, Brown KS. 2013. Model sensitivity and robustness in the estimation of larval transport: a study of particle tracking parameters. J Mar Sys 119–120:19–29. doi: *http://dx.doi.org/10.1016/j.jmarsys.2013.03.004*

Smith LH, Cheng RT. 1987. Tidal and tidally averaged circulation characteristics of Suisun Bay, California. Water Resour Res 23(1):143–155. doi: *http://dx.doi.org/10.1029/WR023i001p00143*

Smith PE. 1997. A three-dimensional, finite-difference model for estuarine circulation [dissertation]. [Davis (CA)]: University of California, Davis.

Sotiropoulos F. 2015. Hydraulics in the era of exponentially growing computing power. J Hydraul Res 53(5):547–562. doi: *http://dx.doi.org/10.1080/00221686.2015.1119210*

Sridharan VK. 2015. Scalar transport in channel networks: development of a particle tracking model to study the movement of scalars in the Sacramento–San Joaquin Delta [dissertation]. [Stanford (CA)]: Stanford University.

Stacey MT, Brennan M, Burau JR, Monismith SG. 2010. The tidally-averaged momentum balance in a partially and periodically stratified estuary. J Phys Ocean 40(11):2418–2434. doi: *http://dx.doi.org/10.1175/2010JPO4389.1*

SWAN Team. 2009. SWAN user manual version 40.72. Delft (Netherlands): Delft University of Technology.

Trowbridge PR, Deas M, Ateljevich E, Danner E, Domagalski J, Enright C, Fleenor W, Foe C, Guerin M, Senn D, Thompson L. 2016. Modeling Science Workgroup white paper: recommendations for a modeling framework to answer nutrient management questions in the Sacramento–San Joaquin Delta. Central Valley Regional Water Quality Control Board.

URS Corporation. 2011. Delta Risk Management Strategy Phase 2 risk reduction report. Building block 1.4: pre-flooding of selected islands. Prepared for the California Department of Water Resources in association with Resource Management Associates. 9 p. Available from: *http://www.water.ca.gov/floodsafe/fessro/levees/drms/docs/DRMS_Phase2_Report_Section6.pdf*

van der Wegen M, Jaffe BE. 2013. Does centennial morphodynamic evolution lead to higher channel efficiency in San Pablo Bay, California? Mar Geol 345:254–265. doi: *http://dx.doi.org/10.1016/j.margeo.2013.06.020*

Wagner RW, Stacey M, Brown LR, Dettinger M. 2011. Statistical models of temperature in the Sacramento–San Joaquin Delta under climate-change scenarios and ecological implications. Estuaries Coasts 34(3):544–556. doi: *http://dx.doi.org/ 10.1007/s12237-010-9369-z*

Wang B, Fringer O, Giddings S, Fong D. 2009. High-resolution simulations of a macrotidal estuary using SUNTANS. Ocean Model 28:167–192. doi: *http://dx.doi.org/doi:10.1016/j.ocemod.2008.08.006*

Wang B, Giddings SN, Fringer OB, Gross ES, Fong DA, Monismith SG. 2011. Modeling and understanding turbulent mixing in a macrotidal salt wedge estuary. J Geophys Res (Oceans) 116(C02036). doi: *http://dx.doi.org/10.1029/2010JC006135*

Weilbeer H. 2005. Numerical simulation and analyses of sediment transport processes in the Ems-Dollard estuary with a three-dimensional model, Chapter 30. In: Kusuda T, Yamanishi H, Spearman J, Gailani JZ, editors. Sediment and ecohydraulics: INTERCOH 2005. Amsterdam (Netherlands): Elsevier.

Whipple AA, Grossinger RM, Rankin D, Stanford B, Askevold RA, 2012. Sacramento–San Joaquin Delta historical ecology investigation: exploring pattern and process. [Internet]. [accessed 2016 July 5]. Richmond (CA): San Francisco Estuary Institute. Available from: *http://www.sfei.org/DeltaHEStudy*

Wolfram PJ, Fringer OB, Monsen N, Gleichauf K, Fong D, Monismith SG. 2016. Modeling intrajunction dispersion at a well-mixed tidal river junction. Hydraul Eng 42(8). doi: *http://dx.doi.org/10.1061/(ASCE)HY.1943-7900.0001108*

Xiu P, Chai F. 2014. Variability of oceanic carbon cycle in the North Pacific from seasonal to decadal scales. J Geophys Res [Oceans] 119(8):5270–5288. doi: *http://dx.doi.org/doi:10.1002/2013JC009505*

Zhang Y, Baptista AM. 2008. SELFE: A semi-implicit Eulerian–Lagrangian finite-element model for cross-scale ocean circulation. Ocean Model 21(3–4):71–96. doi: *http://dx.doi.org/10.1016/j.ocemod.2007.11.005*

Zhang Y, Ateljevich E, Yu H–C, Wu C–H, Yu JCS. 2015. A new vertical coordinate system for a 3D unstructured-grid model. Ocean Model 85:16–31. doi: *http://dx.doi.org/10.1016/j.ocemod.2014.10.003*

Zhang YJ, Ye F, Stanev EV, Grashorn S. 2016.Seamless cross-scale modeling with SCHISM. Ocean Model 102:64–81. doi: *http://dx.doi.org/10.1016/j.ocemod.2016.05.002*

NOTES

Herdman L. 2015. In-person conversation with Stephen Monismith regarding 3–D modeling of temperature in the Delta.

Hamilton D. 2006. E-mail communication to Stephen Monismith regarding modeling of *Microcystis* in lakes.

http://dx.doi.org/10.15447/sfews.2016v14iss4art2